MODELING AND CHARACTERIZATION OF
MULTIPATH FADING CHANNELS IN CELLULAR
MOBILE COMMUNICATION SYSTEMS

A DISSERTATION SUBMITTED IN FULFILMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

BY

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I dedicate this thesis to my wife Warisa and kids Adeer, Palvasha and Ariana for their love and support
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Related Publications

This thesis is based mainly on the following publications:

Journal Papers


**Conference Papers**


[C05] Mohammed T. Simsim, Noor M. Khan, and Predrag B. Rapajic, “Modeling Spatial Aspects of Mobile Channel in Uniformly Distributed Scatters”, in Proc. 8th IEEE International Conf. on Telecommun. (ConTel’05), Zagreb, Croatia, vol. 1, June 2005, pp. 195-201


[C09] Noor M. Khan, and Rodica Ramer, “Effect of Distant Scatterers on MIMO Fading Channel Tracking”, Accepted for publication in Proc. the Progress in Electromagnetic Research Symp. (PIERS’06), Cambridge, USA, March 2006

Environments”, Accepted for publication in *Proc. the Progress in Electromagnetic Research Symp. (PIERS’06)*, Cambridge, USA, March 2006


Abstract

Due to the enormous capacity and performance gains associated with the use of antenna arrays in wireless multi-input multi-output (MIMO) communication links, it is inevitable that these technologies will become an integral part of future systems. In order to assess the potential of such beam-oriented technologies, direct representation of the dispersion of multipath fading channel in angular and temporal domains is required. This representation can only be achieved with the use of spatial channel models. This thesis thus focuses on the issue of spatial channel modeling for cellular systems and on its use in the characterization of multipath fading channels. The results of this thesis are presented mainly in five parts: a) modeling of scattering mechanisms, b) derivation of the closed-form expressions for the spatio-temporal characteristics, c) generalization of the quantitative measure of angular spread, d) investigation of the effect of mobile motion on the spatio-temporal characteristics, and e) characterization of fast fading channel and its use in the signature sequence adaptation for direct sequence code division multiple access (DS-CDMA) system.

The thesis begins with an overview of the fundamentals of spatial channel modeling with regards to the specifics of cellular environments. Previous modeling approaches are discussed intensively and a generalized spatial channel model, the ‘Eccentro-Scattering Model’ is proposed. Using this model, closed-form mathematical expressions for the distributions of angle and time of multipath arrival are derived. These theoretical results for the picocell, microcell and macrocell environments, when compared with previous models and available measurements, are found to be realistic and generic. In macrocell environment, the model incorporates the effect of distant scattering structures in addition to the local ones. Since the angular spread is a key factor of the second order statistics of fading processes in wireless communications, the thesis proposes a novel generalized method of quantifying the angular
spread of the multipath power distribution. The proposed method provides almost all parameters about the angular spread, which can be further used for calculating more accurate spatial correlations and other statistics of multipath fading channels. The degree of accuracy in such correlation calculations can lead to the computation of exact separation distances among array elements required for maximizing capacity in MIMO systems or diversity antennas. The proposed method is also helpful in finding the exact standard deviation of the truncated angular distributions and angular data acquired in measurement campaigns. This thesis also indicates the significance of the effects of angular distribution truncation on the angular spread. Due to the importance of angular spread in the fading statistics, it is proposed as the goodness-of-fit measure in measurement campaigns. In this regard, comparisons of some notable azimuthal models with the measurement results are shown.

The effect of mobile motion on the spatial and temporal characteristics of the channel is also discussed. Three mobile motion scenarios are presented, which can be considered to be responsible for the variations of the spatio-temporal statistical parameters of the multipath signals. Two different cases are also identified, when the terrain and clutter of the mobile surroundings have an additional effect on the temporal spread of the channel during mobile motion. The effect of increasing mobile-base separation on the angular and temporal spreads is elaborated in detail. The proposed theoretical results in spatial characteristics can be extended to characterizing and tracking transient behavior of Doppler spread in time-varying fast fading channels; likewise the proposed theoretical results in temporal characteristics can be utilized in designing efficient equalizers for combating inter-symbol interference (ISI) in time-varying frequency-selective fading channels.

In the last part of the thesis, a linear state-space model is developed for signature sequence adaptation over time-varying fast fading channels in DS-CDMA systems. A decision directed adaptive algorithm, based on the proposed state-space model and Kalman filter, is presented. The algorithm outperforms the gradient-based algorithms in tracking the received distorted signature sequence over time-varying fast fading channels. Simulation results are presented which show that the performance of a linear adaptive receiver can be improved significantly with signature tracking on high Doppler spreads in DS-CDMA systems.
Contents

Acknowledgements iv

Related Publications v

Abstract ix

Table of Contents xi

List of Tables xviii

List of Figures xix

Acronyms xxiii

Notations xxvii

1 Introduction 1

1.1 History of the Capacity Demands in Wireless Communication Systems . . . 1

1.2 Multiantenna Systems . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4

1.2.1 Smart Antenna Systems . . . . . . . . . . . . . . . . . . . . . . . . . . . . 4
1.2.2 MIMO Communication Systems ...................................... 6
1.3 Channel Fading ............................................................. 6
  1.3.1 Mobile Radio Propagation Environment .......................... 6
  1.3.2 Small-Scale Multipath Fading .................................... 8
  1.3.3 Types of Small-Scale Fading ..................................... 11
    1.3.3.1 Based on Multipath Time-Delay Spread .................. 11
    1.3.3.2 Based on Doppler Spread ................................. 13
1.4 Cellular Environments .................................................... 15
  1.4.1 Picocell Environment ............................................. 15
  1.4.2 Microcell Environment .......................................... 17
  1.4.3 Macrocell Environment .......................................... 17
1.5 Capacity of MIMO Systems in Fading Channels .................... 18
1.6 Problem Formulation ..................................................... 21
1.7 Scope of the Thesis and Proposed Methodology .................... 23
1.8 Contributions of the Thesis .......................................... 25

2 A Generalized Spatial Channel Model ................................ 30
  2.1 Introduction ............................................................ 31
    2.1.1 Overview of Physical Spatial Channel Modeling ............ 31
    2.1.2 Previous Work .................................................. 32
    2.1.3 Contributions in the Chapter ................................ 35
2.2 General Channel Modeling Assumptions .................................. 36
2.3 General Channel Modeling Parameters ............................... 39
   2.3.1 Shape of the Scattering Region ................................. 39
      2.3.1.1 Circular Scattering Model ............................. 40
      2.3.1.2 Elliptical Scattering Model ............................ 41
   2.3.2 Distribution of Scatterers ..................................... 41
      2.3.2.1 Uniformly Distributed Scatterers ....................... 41
      2.3.2.2 Gaussian Distributed Scatterers ......................... 42
2.4 The Proposed Eccentro-Scattering Channel Model ............... 43
2.5 The Proposed Jointly Gaussian Scattering (JGSM) Model ....... 46
2.6 Application of the Eccentro-Scattering Model .................... 48
   2.6.1 Picocell Environment ....................................... 48
   2.6.2 Microcell Environment ..................................... 49
   2.6.3 Macrocell Environment ..................................... 52
2.7 Summary of the Chapter ........................................... 53

3 Modeling Spatial Characteristics of Mobile Channel .......... 54
   3.1 Overview .................................................... 55
   3.2 Angle Of Arrival For Picocell And Microcell Environments .... 56
      3.2.1 Uniformly Distributed Scatterers ....................... 58
      3.2.2 Gaussian Distributed Scatterers ......................... 59
5.1 Overview ................................................................. 117
  5.1.1 Background ...................................................... 117
  5.1.2 Problem Formulation .......................................... 118
  5.1.3 Contributions ................................................ 119
5.2 Model Description ................................................. 120
5.3 pdf of ToA for Picocells and Microcells ......................... 124
5.4 pdf Of ToA for Macrocells ........................................ 128
  5.4.1 Local Scatterers ............................................... 131
  5.4.2 Distant Scatterers ........................................... 134
5.5 Conclusions ....................................................... 137

6 Effect of Mobile Motion on the Spatio-Temporal Characteristics 139
  6.1 Overview ............................................................ 140
  6.2 Mobile Motion Scenarios ........................................ 141
  6.3 Behavior of Spatial Characteristics under Mobile Motion .... 144
    6.3.1 Important Spatial Parameters ............................. 144
    6.3.2 Effect of Mobile Motion on the Spatial Characteristics of the Channel 147
      6.3.2.1 Picocell and Microcell Environments ................. 147
      6.3.2.2 Macrocell Environments .............................. 151
  6.4 Behavior of Temporal Characteristics under Mobile Motion ... 159
    6.4.1 Temporal Channel Model .................................. 159
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4.2</td>
<td>Some Important Temporal Parameters</td>
<td>161</td>
</tr>
<tr>
<td>6.4.3</td>
<td>Lifetime of Scatterers</td>
<td>162</td>
</tr>
<tr>
<td>6.4.3.1</td>
<td>Case 1</td>
<td>163</td>
</tr>
<tr>
<td>6.4.3.2</td>
<td>Case 2</td>
<td>165</td>
</tr>
<tr>
<td>6.4.4</td>
<td>Effect of Mobile Motion on ToA Statistics</td>
<td>167</td>
</tr>
<tr>
<td>6.4.4.1</td>
<td>Picocell and Microcell Environments</td>
<td>167</td>
</tr>
<tr>
<td>6.4.4.2</td>
<td>Macrocell Environments</td>
<td>169</td>
</tr>
<tr>
<td>6.5</td>
<td>Conclusion</td>
<td>171</td>
</tr>
<tr>
<td>7</td>
<td>Fast Fading Channel Modeling for Single-Carrier DS-CDMA Systems</td>
<td>173</td>
</tr>
<tr>
<td>7.1</td>
<td>Overview</td>
<td>174</td>
</tr>
<tr>
<td>7.1.1</td>
<td>History of DS-CDMA Detectors</td>
<td>174</td>
</tr>
<tr>
<td>7.1.2</td>
<td>Time-Varying Nature of the DS-CDMA Channel</td>
<td>179</td>
</tr>
<tr>
<td>7.1.3</td>
<td>Contributions of the Chapter</td>
<td>180</td>
</tr>
<tr>
<td>7.2</td>
<td>State-Space Approach in Multipath Fading Channel Modeling</td>
<td>181</td>
</tr>
<tr>
<td>7.2.1</td>
<td>Characterization of Multipath Fading Channels</td>
<td>182</td>
</tr>
<tr>
<td>7.2.2</td>
<td>State-Space Model of the Communication System over Fast Fading Multipath Channels</td>
<td>189</td>
</tr>
<tr>
<td>7.3</td>
<td>Kalman Filter Based Adaptive Detection for DS-CDMA System</td>
<td>189</td>
</tr>
<tr>
<td>7.3.1</td>
<td>System Model</td>
<td>190</td>
</tr>
<tr>
<td>7.3.1.1</td>
<td>Channel Model</td>
<td>191</td>
</tr>
</tbody>
</table>
7.3.1.2 Receiver Model ........................................... 194

7.3.2 Kalman Filter-Based Signature Sequence Tracking .................. 196

7.3.2.1 State-Space Model for the Adaptive Multiuser Detection .... 199

7.3.2.2 Signature Sequence Estimation Algorithm .................... 199

7.3.3 Modes of Operation ......................................... 201

7.3.3.1 Decision Directed (DD) mode .............................. 201

7.3.3.2 Training Directed (TD) and DD mode ....................... 202

7.3.3.3 TD and Non-Estimation (NE) mode ........................ 202

7.3.3.4 Repeated TD and NE mode ................................ 202

7.3.4 Simulation Results ............................................ 203

7.4 Conclusions ..................................................... 208

8 Conclusions and Future Work ................................... 209

8.1 Summary of the Thesis ........................................ 210

8.2 Conclusions and Future Work .................................. 214
List of Tables

2.1 Typical Values of the Parameters for Picocell and Microcell Environments Based on the Eccentro-Scattering Model .......................... 50

2.2 Typical Values of the Parameters for Macrocell Environments Based on the Eccentro-Scattering Model .......................... 51

3.1 Summary of the Spatial Channel Models ........................................ 78

3.2 Values of $R_{\text{null}}$ for different macrocell environments ................. 86
List of Figures

1.1 Typical outdoor multipath propagation environment .................. 8

1.2 Illustration of Doppler effect ............................................. 10

1.3 Types of small-scale fading ................................................. 14

1.4 Multipath scattering in (a) Picocell (Indoor), (b) Microcell (Outdoor), and (c) Macrocell (Outdoor) Environments ............................ 16

1.5 Illustration of the Proposed Dissertation Methodology ............. 24

2.1 Typical multipath fading environment ................................. 36

2.2 Modeling with respect to the shape of the scattering region for uniform scatterer distribution .................................................. 40

2.3 Modeling with respect to the Gaussian scatterer distribution .......... 42

2.4 Elliptical diagram ............................................................. 44

2.5 Jointly Gaussian Scattering Model (JGSM) ............................... 47

2.6 Typical (a) Picocell and (b) Microcell Environments in Gaussian distributed scattering ............................. 49

3.1 Eccentro-Scattering model in uniform scattering ..................... 57

3.2 Eccentro-Scattering model in Gaussian scattering ..................... 60
3.3 Effect of increasing $a$ with respect to $\sigma_{MS}$ on the pdf of AoA in picocells and microcells, $\sigma_{BS}=0$. ................................................................. 63

3.4 Effect of increasing $\sigma_{MS}$ with respect to $a$ on the pdf of AoA in picocells and microcells, $\sigma_{BS}=0$. ................................................................. 65

3.5 Comparison of the pdf in AoA for the Eccentro-Scattering model, and Laplacian function with measurements [1]. ................................................................. 66

3.6 Typical macrocell environment ................................................................. 68

3.7 Simulated and theoretical pdf of AoA for suburban macrocell with $d=2000m$, $a=300m$, $D=5000m$, $a_{D}=150m$, and $\theta_{D}=15^\circ$. ................................................................. 74

3.8 The proposed scattering model ................................................................. 80

3.9 pdf of AoA at BS in urban macrocell mobile environments ......................... 84

4.1 Comparison between truncated ($\theta_{\text{span}}=90^\circ$) and untruncated ($\theta_{\text{span}}=360^\circ$) Gaussian density functions, $\sigma_{g}=30^\circ$, $\bar{\theta}=45^\circ$. ................................................................. 96

4.2 Effect of Gaussian distribution truncation on the angle spread ...................... 98

4.3 Comparison between truncated ($\theta_{\text{span}}=90^\circ$) and untruncated ($\theta_{\text{span}}=360^\circ$) Laplacian density functions, $\sigma_{l}=30^\circ$, $\bar{\theta}=45^\circ$. ................................................................. 99

4.4 Effect of Laplacian distribution truncation on the angle spread .................... 101

4.5 The factors which cause truncation of the Gaussian distribution in AoA .......... 104

4.6 Comparison of the distribution in AoA for the candidate models (Eccentro-Scattering Model [section 3.2], Gaussian [2] and Uniform Elliptical Scattering Model [3]) with the measurements [1] and simulations in indoor environments ......................... 108

4.7 Comparison of the distribution in AoA for the candidate models (Eccentro-Scattering Model [section 3.2], Laplacian [1] and Raised-Laplacian) with the measurements [1] in indoor environments .................................................. 109
4.8 Comparison of the distribution in AoA for the candidate models (GSDM [2] and JGSM [section 3.4]) with the measurements [4] in outdoor environments 110

5.1 Geometry of the proposed temporal channel model 121
5.2 Temporal model for a typical multipath fading environment 121
5.3 Proposed temporal channel model for picocells and microcells 125
5.4 pdf of ToA for picocell and microcell environments 127
5.5 Temporal channel model for macrocells 130
5.6 pdf of ToA for macrocells with the effect of distant scatterers 136

6.1 Illustration of motion scenarios 142
6.2 Microcell and picocell environments 146
6.3 Effect of MS motion on the pdf of AoA, various line styles show the plots at three different MS positions 148
6.4 Behavior of $\theta_{\text{span}}$, $\bar{\theta}$ and $\sigma_\theta$ under the effect of MS motion in microcell and picocell environments 149
6.5 Behavior of $S_0$ and $\Lambda$ under the effect of MS motion in microcell and picocell environments 150
6.6 Macrocell environment 152
6.7 Behavior of $\theta_{\text{span}}$, $\bar{\theta}$ and $\sigma_\theta$ under the effect of MS motion in macrocell environment 154
6.8 Collective effect of distant scattering cluster and MS motion on the spatial spread of cellular mobile channel in macrocell environment 156
6.9 Behavior of $S_0$ and $\Lambda$ under the effect of MS motion in macrocell environment 157
Acronyms

1G        First Generation (of Land Mobile Systems)
2G        Second Generation (of Land Mobile Systems)
3G        Third Generation (of Land Mobile Systems)
3GPP      Third Generation Partnership Project
2-D       Two Dimensional
3-D       Three Dimensional
1xRTT     1x Radio Transmission Technology
AMPS      Advanced Mobile Phone Services
AoA       Angle of Arrival
AR        Autoregressive
ARMA      Autoregressive Moving-Average
AT&T      American Telephone and Telegraph
AWGN      Additive White Gaussian Noise
BER       Bit Error Rate
BLAST     Bell Labs Layered Space-Time
BPSK      Binary Phase Shift Keying
BS        Base Stations
BW        Bandwidth
CCI       Co-Channel Interference
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF</td>
<td>Cumulative Distribution Function</td>
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<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
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<td>CSI</td>
<td>Channel State Information</td>
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<td>DCM</td>
<td>Directional Channel Model</td>
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<td>DD</td>
<td>Decision Directed</td>
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<td>DS</td>
<td>Delay Spread</td>
</tr>
<tr>
<td>DS-CDMA</td>
<td>Direct-Sequence Code Division Multiple Access</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
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<tr>
<td>FM</td>
<td>Frequency Modulation</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency-Shift Keying</td>
</tr>
<tr>
<td>GBSBM</td>
<td>Geometrically-Based Single Bounce Macrocell</td>
</tr>
<tr>
<td>GSDM</td>
<td>Gaussian Scatter Density Model</td>
</tr>
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<td>GSM</td>
<td>Global System for Mobile</td>
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<td>HIPERLAN</td>
<td>High Performance Radio Local Area Network</td>
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<tr>
<td>iid</td>
<td>independent identically distributed</td>
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<td>IMT</td>
<td>International Mobile Telecommunications</td>
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<td>ISI</td>
<td>Inter-Symbol Interference</td>
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<td>JGSM</td>
<td>Jointly Gaussian Scattering Model</td>
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<td>LoS</td>
<td>Line of Sight</td>
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<td>LMS</td>
<td>Least Mean Square</td>
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<td>MA</td>
<td>Moving-Average</td>
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<td>MAI</td>
<td>Multiple Access Interference</td>
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<td>MAP</td>
<td>Maximum A Posteriori</td>
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<td>MC</td>
<td>Multi-Carrier</td>
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<td>MF</td>
<td>Matched Filter</td>
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<tr>
<td>MIMO</td>
<td>Multiple-Input Multiple-Output</td>
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<tr>
<td>Acronym</td>
<td>Definition</td>
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<tr>
<td>---------</td>
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</tr>
<tr>
<td>MLMR</td>
<td>Maximum Likelihood Multiuser Receiver</td>
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<td>MMSE</td>
<td>Minimum Mean Squared Error</td>
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<tr>
<td>MRC</td>
<td>Maximum Ratio Combining</td>
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<tr>
<td>MS</td>
<td>Mobile Station</td>
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<td>NE</td>
<td>Non-Estimation</td>
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<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<tr>
<td>OTD</td>
<td>Orthogonal Transmit Diversity</td>
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<tr>
<td>PAS</td>
<td>Power Azimuthal Spectrum</td>
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<tr>
<td>pdf</td>
<td>Probability Density Function</td>
</tr>
<tr>
<td>PSK</td>
<td>Phase Shift Keying</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
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<tr>
<td>QoS</td>
<td>Quality of Service</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>RLS</td>
<td>Recursive Least Squares</td>
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<tr>
<td>rms</td>
<td>Root Mean Square</td>
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<tr>
<td>SD</td>
<td>Standard Deviation</td>
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<tr>
<td>SDMA</td>
<td>Space Division Multiple Access</td>
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<tr>
<td>SINR</td>
<td>Signal-to-Interference plus Noise Ratio</td>
</tr>
<tr>
<td>SM</td>
<td>Spatial Multiplexing</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-Noise Ratio</td>
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<tr>
<td>ST</td>
<td>Space-Time</td>
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<td>TD</td>
<td>Training Directed</td>
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<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
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<tr>
<td>ToA</td>
<td>Time of Arrival</td>
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<tr>
<td>UHF</td>
<td>Ultra-High Frequency</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication Systems</td>
</tr>
<tr>
<td>V-BLAST</td>
<td>Vertical Bell Laboratories Layered Space-Time</td>
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<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<tr>
<td>WLMS</td>
<td>Wiener Least Mean Square</td>
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<tr>
<td>WSSUS</td>
<td>Wide-Sense Stationary Uncorrelated Scattering</td>
</tr>
</tbody>
</table>
## Notations

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Boldface capital letters</strong></td>
<td>matrices</td>
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<tr>
<td><strong>Boldface small letters</strong></td>
<td>vectors</td>
</tr>
<tr>
<td><strong>Capital letters</strong></td>
<td>points on a geometrical diagram or scalar quantities</td>
</tr>
<tr>
<td><strong>Small letters</strong></td>
<td>scalar quantities</td>
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<tr>
<td>$(·)^T$</td>
<td>transpose</td>
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<tr>
<td>$(·)^*$</td>
<td>conjugate</td>
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<tr>
<td>$(·)^H$</td>
<td>Hermitian transpose</td>
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<tr>
<td>$s * h$</td>
<td>convolution between $s$ and $h$</td>
</tr>
<tr>
<td>$\text{tr}(·)$</td>
<td>trace</td>
</tr>
<tr>
<td>$\mathbb{E}(·)$</td>
<td>expectation</td>
</tr>
<tr>
<td>$\text{diag}(x)$</td>
<td>diagonal matrix with $x$ on its diagonal</td>
</tr>
<tr>
<td>$</td>
<td>·</td>
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<tr>
<td>$| · |$</td>
<td>Frobenius-norm</td>
</tr>
<tr>
<td>$\Re{·}$</td>
<td>real part of a complex number</td>
</tr>
<tr>
<td>$\Im{·}$</td>
<td>imaginary part of a complex number</td>
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<tr>
<td>$\mathbf{I}_N$</td>
<td>identity matrix of size $N$</td>
</tr>
<tr>
<td>$a_i$</td>
<td>$i$th element of vector $a$</td>
</tr>
</tbody>
</table>

xxvii
\( a_{ij} \) (\( i, j \)th element of matrix \( A \))

\( \mathbf{a}_k \) vector \( \mathbf{a} \) belonging to \( k \)th user

\( \mathbf{A}_k \) matrix \( \mathbf{A} \) belonging to \( k \)th user

\( \mathbb{R} \) the set of real numbers

\( \mathbb{C} \) the set of complex numbers
Chapter 1

Introduction

This chapter first gives a brief overview of wireless communications. The background and motivations for the research work in this thesis are described. A concise outline for the thesis is provided at the end of this chapter.

1.1 History of the Capacity Demands in Wireless Communication Systems

Capacity enhancement has always been an important issue in wireless communication systems. The demand for more capacity was realized even, when the first 2 MHz land mobile radiotelephone system was installed by the Detroit Police Department in 1921 for Police car dispatch. This was the beginning of the civilian use of wireless technology. The problem
1.1 History of the Capacity Demands in Wireless Communication Systems

of the lack of channels in the low frequency band was initially tackled in 1933, with the use of higher frequency bands and the invention of Frequency Modulation (FM). In 1946, a Personal Correspondence System introduced by Bell Systems began service and operated at 150 MHz with speech channels 120 KHz apart [5]. As demand for public wireless services began to grow, the Improved Mobile Telephone Service (IMTS) using FM technology was developed by AT&T.

The Cellular concept, conceived by D. H. Ring at Bell Laboratories in 1947, paved the way for the modern cellular mobile communication systems [6] and later inspired AT&T to propose its first high capacity analog cellular telephone system called the Advanced Mobile Phone Service (AMPS) in 1968-70. AMPS was the first U.S. cellular telephone system, and was deployed in late 1983 by Ameritech in Chicago, IL [7, 8]. In AMPS, radio systems rely on judicious frequency re-use plans and frequency division multiple access (FDMA) to maximize capacity. The analog cellular mobile systems of that age, altogether, are known as the First Generation (1G) wireless technologies. Mobile systems have evolved rapidly since then, incorporating digital communication technology and have thus transformed into the new era of the Second Generation (2G) wireless technologies. This era includes the Global System for Mobiles (GSM), IS-136, and IS-95. In order to maximize capacity or to accommodate a large number of users, the former two standards use time division multiple access (TDMA), while the latter one uses code division multiple access (CDMA).

With the increasing use of the internet in the late 1990s, the demand for higher spec-
1.1 History of the Capacity Demands in Wireless Communication Systems

tral efficiency and data rates has led to the development of the Third Generation (3G) wireless technologies [5]. 3G offers Universal Mobile Telecommunication Systems (UMTS), i.e., wideband CDMA and 1xRTT, i.e., CDMA-2000 as the primary standards. The 1X in 1xRTT refers to 1x the number of 1.25MHz channels and RTT in 1xRTT stands for Radio Transmission Technology. In order to satisfy the higher-rate requirements of modern data services, the narrow-band 2G systems are being upgraded to 3G cellular systems and wideband wireless local area networks (WLANs). Limitations in the radio frequency (RF) spectrum necessitate the use of some innovative techniques to meet the increased demand in data rate, quality of service (QoS) [5] and capacity. The innovative technique, which opened a new dimension - space and pledged to improve the performance substantially, is the use of multiple antennas at the transmitter and/or receiver in a wireless communication link. In the mid 1990s, multiple transmit and receive antennas were incorporated effectively for the first time, to establish a highly spectral efficient communication system - BLAST [9]. The system was highly robust in highly scattering environments, with the assumption that the signals arriving from the individual transmit antennas at each of the receive antennas are uncorrelated. Soon V-BLAST was introduced with more improvements [10], but spectral efficiency was, still dependent on the signal correlations.
1.2 Multiantenna Systems

As spectrum became a more and more precious resource, researchers investigated ways of increasing the capacity of wireless systems without actually increasing the required spectrum. Multiantenna systems offer such a possibility. Multiantenna systems can be grouped into two categories on the basis of multiantenna element deployment [11]:

1. Smart Antenna systems, where multiantenna elements are deployed at one link end only.

2. Multiple-Input Multiple-Output (MIMO) systems, where multiantenna elements are deployed at both link ends.

1.2.1 Smart Antenna Systems

These are the antennas with multiple elements, where signals from different elements are combined/created by an adaptive (intelligent) algorithm. When a smart antenna is deployed at the receiver, the signals are combined; for the transmitter case, the signals are created [11]. In most practical situations, smart antennas are deployed at the BS. Smart antennas exploit the directional properties of the channel; hence, they provide spatial diversity with smartness.

Increasing the capacity is the most important application of smart antennas. They achieve this goal through the following approaches:
1.2 Multiantenna Systems

Spatial Filtering for Interference Reduction: This is used in TDMA/FDMA systems to reduce the reuse distance. A conventional TDMA/FDMA system cannot reuse the same frequency in each neighboring cell, since the interference from the adjacent cells would be too strong [11]. Smart antennas reduce interference and hence help in reducing the reuse distance. This leads to an improvement in total spectral efficiency.

Space Division Multiple Access (SDMA): In this method, reuse distance remains unchanged, while the number of users within a given cell is increased. SDMA controls the radiated energy for each user in space and serves different users by using spot beam smart antennas. Multiple users can be accommodated on the same time/frequency slot (TDMA/FDMA), because the BS distinguishes them at different locations by means of their different spatial signatures. SIR is increased for the desired users and hence capacity of the whole system is increased [12].

Capacity increase in CDMA systems: In these systems, smart antennas enhance the received signal power and hence the number of admissible users is increased in the cell. The number of admissible users in the cell increases linearly with the number of antenna elements, in ideal channel conditions.

Capacity increase in 3G CDMA systems: In 3G networks, high-rate data transmission is considered an important application. So users and interferers are usually allocated low spreading factors. Hence, smart antennas have to use the spatial filtering approach in these systems. Thus, they reduce the interference of the desired user by
1.3 Channel Fading

placing a null in the direction of the interferer [11].

1.2.2 MIMO Communication Systems

A large suite of techniques, known collectively as MIMO communications, have been developed in the past several years to exploit effectively the resulting multi-dimensionality, when multiple antennas are used at both ends of the wireless communication link.

Since multiple antennas in MIMO systems can also serve as one-sided smart antennas, MIMO systems are able to accomplish the tasks of smart antennas. Therefore, besides all those applications meant for smart antennas, MIMO systems can also be used for spatial multiplexing. Spatial multiplexing allows direct improvement of capacity by simultaneous transmission of multiple datastreams in parallel.

1.3 Channel Fading

1.3.1 Mobile Radio Propagation Environment

Radio signals generally propagate according to three mechanisms:

1. Reflection

2. Diffraction
3. Scattering

Reflections arise when plane waves are incident upon a surface with dimensions that are very large compared to the wavelength. Diffraction occurs according to Huygen’s principle when there is an obstruction between the transmitter and receiver antennas, and secondary waves are generated behind the obstructing body. Scattering occurs when the plane waves are incident upon an object whose dimensions are on the order of a wavelength or less, and causes the energy to be redirected in many directions [8, 13].

The above three mechanisms give rise to three nearly independent phenomena in radio channel:

1. Path-loss
2. Shadowing
3. Multipath Fading

*Path-loss* is the variation of the signal strength with the distance, while *shadowing* occurs, when the signal is obstructed by a huge terrain feature such as skyscrapers and hills. Most cellular systems operate in urban areas where there is no direct line-of-sight (LoS) path between BS and MS, therefore the presence of high-rise buildings causes severe diffraction loss. Due to multiple reflections from various objects, the electromagnetic waves travel along different paths of varying lengths. The interaction between these waves causes *multipath fading*
at a specific location. Each of these phenomena is caused by a different underlying physical principle and each must be accounted for when designing and evaluating the performance of a cellular system.

Each of the above mentioned wave propagation phenomena has its own importance in designing and evaluating the performance of a cellular system. However, the carrier wavelength used in UHF mobile radio applications typically ranges from 15 to 60 cm. Therefore, small changes in differential propagation delays due to MS mobility will cause large changes in the phases of the individually arriving plane waves. Hence, multipath fading can be considered the most important wave propagation phenomenon, which causes small-scale fading effects. In Fig. 1.1, a typical outdoor multipath propagation environment is shown, where MS receives many replicas of the transmitted signal, with different delays.

### 1.3.2 Small-Scale Multipath Fading

The three most important small-scale fading effects of multipath in the radio channel are [8]:

- **Shadowing:**
- **NLOS (Non-Line-of-Sight):**
- **Multipath:**

Figure 1.1: *Typical outdoor multipath propagation environment*
1.3 Channel Fading

1. Rapid changes in signal strength over a small travel distance or time interval

2. Time dispersion (echoes) caused by multipath propagation delays

3. Random frequency modulation due to varying Doppler shifts on different multipath signals.

Multipath fading results in rapid variations in the envelope of the received signal and is caused when plane waves arrive from many different directions with random phases and combine vectorially at the receiver antenna. Typically the received envelope can vary by as much as 30 to 40 dB over a fraction of a wavelength due to constructive and destructive addition [13].

Multipath also causes time dispersion, because the multiple replicas of the transmitted signal propagate over different transmission paths and reach the receiver antenna with different time delays. The most important parameters of time dispersion of the channel are mean excess delay and rms delay spread. Analogous to the delay spread parameters in time domain, coherence bandwidth, $B_C$, is used to characterize the channel in the frequency domain. Coherence bandwidth is a statistical measure of the range of frequencies over which the channel can be considered flat (i.e., a channel which passes all spectral components with approximately equal gain and linear phase) [8].

Due to the relative motion between the mobile and the base station, each multipath wave experiences an apparent shift in frequency. The shift in received signal frequency due to
1.3 Channel Fading

Figure 1.2: Illustration of Doppler effect

motion is called the *Doppler shift*, and is directly proportional to the velocity and direction of motion of the mobile with respect to the direction of arrival of the received multipath wave. Thus, the Doppler shift can be written as,

\[
f_d = \frac{v}{\lambda} \cos \psi
\]

\[
= \frac{vf_c}{c} \cos \psi
\]

(1.1)

where \(v\) is the speed of the mobile, \(\psi\) is the direction of motion of the mobile with respect to the direction of arrival of the multipath and \(\lambda\) and \(f_c\) are the wavelength and carrier frequency of the radio signal, respectively. Fig. 1.2 illustrates the Doppler effect on the mobile channel in small-scale fading environment.

Since the angle of arrival of the multipath signal at MS varies constantly, Doppler shift causes random frequency modulation of the radio signal at each instant of time. When a pure sinusoidal frequency \(f_c\) is transmitted, the received signal spectrum, called the Doppler
1.3 Channel Fading

spectrum, will have components in the range $f_c - f_d$ to $f_c + f_d$. This spectral broadening can be quantified by *Doppler spread*. Doppler spread is the measure of the spectral broadening caused by the time rate of change of the mobile radio channel and is defined as the range of frequencies over which the received Doppler spectrum is essentially non-zero [8]. If the baseband signal bandwidth is much greater than the Doppler spread, the effects of Doppler spread are negligible at the receiver. This is a slow fading channel. Coherence time, $T_C$, is the time domain dual of the Doppler spread and is used to characterize the time-varying nature of the frequency dispersiveness of the channel in the time domain.

1.3.3 Types of Small-Scale Fading

Since small-scale fading channels are characterized by their time-dispersion and time-varying nature, small-scale fading can thus be categorized on the basis of delay and Doppler spreads [8, 11, 13]. However, another type of dispersion called spatial dispersion also has a significant effect on the mobile channel, especially when a multiantenna system, discussed in the previous section, is used at one or both link ends. Large multipath angular spreads can induce space-selective fading in multiantenna or directional communication channels.

1.3.3.1 Based on Multipath Time-Delay Spread

**Flat Fading:** If the mobile radio channel has a constant gain and linear phase response over a bandwidth which is greater than the bandwidth of the transmitted signal, then
1.3 Channel Fading

the received signal will undergo *frequency flat fading* or simply, *flat fading*. This type of fading is historically the most common type of fading described in the technical literature. Flat fading channels are also known as *amplitude varying channels* and are sometimes referred to as *narrowband channels*, since the bandwidth of the applied signal, $B_S$, is narrow as compared to the channel flat fading bandwidth or the Coherence bandwidth, $B_C$. To summarize, a signal undergoes flat fading if

$$B_S << B_C$$  \hspace{1cm} (1.2)

and

$$T_S >> \sigma_\tau$$  \hspace{1cm} (1.3)

where $B_S$ and $T_S$ are the bandwidth and symbol duration of the transmitted signal and $\sigma_\tau$ is the rms value of the delay spread.

**Frequency Selective Fading:** If the channel possesses a constant-gain and linear phase response over a bandwidth that is smaller than the bandwidth of transmitted signal, then the channel creates *frequency selective fading* on the received signal. Under such conditions, the channel impulse response has a multipath delay spread which is greater than the reciprocal bandwidth of the transmitted message waveform. When this occurs, the received signal includes multiple versions of the transmitted waveform which are attenuated (faded) and delayed in time, and hence the received signal is distorted.

Thus the channel induces *intersymbol interference* (ISI) [8]. For frequency selective fading, the spectrum $S(f)$ of the transmitted signal has a bandwidth which is greater
1.3 Channel Fading

than the coherence bandwidth $B_C$ of the channel. To summarize, a signal undergoes frequency selective fading if [8]

$$B_S > B_C$$  \hspace{1cm} (1.4)$$

and

$$T_S < \sigma_\tau$$  \hspace{1cm} (1.5)$$

1.3.3.2 Based on Doppler Spread

Depending on how rapidly the transmitted baseband signal changes as compared to the rate of change of the channel, a channel may be classified as a fast fading or slow fading channel.

**Fast Fading or Time Selective Fading:** If the channel impulse response changes rapidly within the symbol duration, then the channel is said to be a fast fading channel. Under such conditions, the coherence time of the channel is smaller than the symbol period of the transmitted signal. This causes frequency dispersion (also called time-selective fading) due to Doppler spreading, which leads to signal distortion. Viewed in the frequency domain, signal distortion due to fast fading increases with increasing Doppler spread relative to the bandwidth of the transmitted signal. Therefore, a signal undergoes fast fading or time selective fading if [8]

$$T_S > T_C$$  \hspace{1cm} (1.6)$$
1.3 Channel Fading

and

\[ B_S < B_D \] (1.7)

where \( B_D \) is the Doppler spread of the channel.

**Slow Fading:** In a *slow fading* or *time-flat fading* channel, the channel impulse response changes at a rate much slower than the transmitted baseband signal. In this case, the channel may be assumed to be static over one or several reciprocal bandwidth intervals. In the frequency domain, this implies that the Doppler spread of the channel is much less than the bandwidth of the baseband signal. Therefore, a signal undergoes slow fading or time-flat fading if [8]

\[ T_S << T_C \] (1.8)

and

\[ B_S >> B_D \] (1.9)

Figure 1.3: *Types of small-scale fading*
1.4 Cellular Environments

A typical cellular radio system consists of a collection of fixed base stations (BSs) that define the radio coverage areas or cells\(^1\). The height and placement of the BS antennas affect the proximity of local scatterers at the BS [13]. Radio environments have extremely different geographical and electrical features, which in turn lead to different propagation mechanisms. These propagation mechanisms have been grouped into three categories based on the cell type, i.e. picocell, microcell, and macrocell. However, there would still be variability within these categories due to other factors such as the differences in antenna heights, average height of the surrounding buildings, total number of users, distance between users, size of the coverage area, and density of scatterers, etc.

1.4.1 Picocell Environment

In the picocell environment, BS and MS, both surrounded by scatterers, are a few meters away from each other (see Fig. 1.4(a)). The antenna heights are relatively low and the scatterers are assumed to exist near BS as likely as near MS. This situation mainly occurs in indoor wireless communication, e.g. offices and factory halls, and it may include street crossings under some circumstances. Wireless Local Area Networks (WLANs) are also good examples of picocell environment.

\(^1\)In military applications the BSs may be moving
1.4 Cellular Environments

(a) Scatterers common to both MS and BS (Equally Influential)

(b) Scatterers local to both MS and BS (Influential)

(c) Remote Dominant Reflectors/Scatterers (Influential)

Scatterers local to BS (Non-influential)

Scatterers local to MS (Influential)

Elevated BS Antenna

Figure 1.4: Multipath scattering in (a) Picocell (Indoor), (b) Microcell (Outdoor), and (c) Macrocell (Outdoor) Environments
1.4 Cellular Environments

1.4.2 Microcell Environment

In the Microcell environment, the distance between BS and MS is greater than that in picocells (but less than a hundred meters [14]). Here also antenna heights are relatively low and multipath scattering is assumed near BS. However BS possesses usually fewer scattering points in its vicinity compared to MS (see Fig. 1.4(b)). This situation corresponds mostly to streets, shopping malls, busy roads, and downtown areas.

1.4.3 Macrocell Environment

In the macrocell environment, BS is usually located far from MS in the order of kilometers. This environment often refers to BS locations over rooftops [14]. The BS antenna height is greater than the surrounding buildings/scatterers, and therefore, it is viable to assume no scatterers in the vicinity of BS. Hence, the received signal at BS results predominantly from the local scattering process in the vicinity of MS [15] and the distant scattering process in the transmission path between BS and MS. Rural, suburban, and hilly areas are the best examples of the macrocell environment. Fig. 1.4(b) depicts a typical macrocellular environment. Here, the spatial parameters are the functions of two major aspects, namely:

**Local scattering:** This is the scattering process which occurs in the vicinity of MS (it is normally influenced by MS speed).

**Distant or remote scattering:** This is the scattering process which results from the dom-
inant distant scattering structures far from both BS and MS. This type of scattering can occur in hilly and suburban areas due to large scattering structures such as mountains and high-rise building clusters, which have a significant influence on the mobile channel. Even though these large scattering structures are far away from both BS and MS, they can act as discrete reflectors or clustered reflectors [16]. In a ‘bad urban’ environment, a two-cluster model is more appropriate [14], where distant or remote scatterers are usually the high-rise buildings.

1.5 Capacity of MIMO Systems in Fading Channels

In the early years of MIMO research, the main emphasis was on information-theoretic limits. After 2000, emphasis shifted more to the question of how the theoretical gains of MIMO systems can be realized in practice. Capacity of the MIMO systems is strictly dependent on the channel fading. Following the landmark work done by Claude E. Shannon [17], Foschini et al. has derived the capacity equation for MIMO systems in non-fading channels [18]. The information-theoretic capacity for single antenna system, over AWGN channels, is [11]:

\[
C_{\text{shannon}} = \log_2 \left( 1 + \gamma |h|^2 \right)
\]  

(1.10)

where \( \gamma \) is the SNR at the receiver and \( h \) is the normalized transfer function from the transmitter to the receiver. In the frequency-flat case, \( h \) is just a scalar number. It is obvious from equation (1.10) that capacity increases only logarithmically with the SNR, so
that boosting the transmitter power is a highly ineffective way of increasing capacity.

Now consider the case of MIMO, where the channel is represented by a complex channel transfer matrix $H$, whose entries $h_{ij}$ correspond to the response of the $i$th receiver to the signal sent by the $j$th transmitter. Thus the matrix $H$ can be written as,

$$H = \begin{pmatrix} h_{11} & h_{12} & \cdots & 0 \\ h_{21} & h_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ h_{N_r,1} & h_{N_r,2} & \cdots & h_{N_r,N_t} \end{pmatrix} \quad (1.11)$$

where $N_r$ and $N_t$ are the number of receive and transmit antennas. The received signal vector

$$r = Hs + n \quad (1.12)$$

is received by $N_r$ antenna elements, where $s$ is the transmit signal vector and $n$ is the AWGN noise vector. The capacity equation for the MIMO system shown in (1.12) can be written as [11],

$$C_{\text{MIMO}} = \log_2 \left[ \det \left( I_{N_r} + \frac{\bar{\gamma}}{N_t} HR_{\text{ss}}H^H \right) \right] \quad (1.13)$$

where $I_{N_r}$ is the $N_r \times N_r$ identity matrix, $\bar{\gamma}$ is the mean SNR per receiver antenna element, and $R_{\text{ss}}$ is the correlation matrix of the transmit data. It is evident from equation (1.13) that capacity increases linearly with $\min(N_t, N_r, N_s)$, where $N_s$ is the number of significant parallel paths in space on which data-streams from transmit antennas are transmitted to the receive antennas.
It is also evident from equation (1.13) that channel matrix plays an important role in increasing the capacity of a MIMO communication system. If channel is Rayleigh-fading, and fading is independent at different antenna elements, the $h_{ij}$ entries are iid zero-mean, circularly symmetric complex Gaussian random variables with unit variance, i.e., the real and imaginary part each has variance $1/2$. Suppose that a large number of multipath components of approximately equal strength exist and there is sufficient distance between antenna elements. Then, the power carried by each $h_{ij}$ is chi-square-distributed with 2 degrees of freedom. Since fading is independent, there is high probability that the channel matrix $H$ is full rank and the eigenvalues are fairly similar to each other; consequently, capacity increases linearly with the number of antenna elements. Thus, the existence of heavy multipath, which is usually considered a drawback, becomes a major advantage in MIMO systems [11].

On the other hand, the high spectral efficiency of the MIMO systems is significantly reduced if the signals arriving at the receivers are correlated [19]. As the BS is usually placed above local clutter, the angular spectrum incident on the base is narrow, inducing correlation among BS signals, which reduces the capacity of the MIMO system. Maximum capacity can only be achieved when $\langle h_{ij} h_{kl}^* \rangle = 0$ for $i \neq k$ and for $j \neq l$.

Unfortunately, all channels occurring in practice are not ideal, as discussed in section 1.3. They are more complicated and their deviations from the idealized assumptions can have significant impact on the capacity [11,20].
1.6 Problem Formulation

As discussed earlier, correlations of the signals at different antenna elements can significantly reduce the capacity of a MIMO system. Actually, correlations of the signals force the spread in the singular values of the channel matrix, $H$, lowering the SNRs of some of the parallel channels.

Correlation is influenced by the angular spectrum of the channel as well as the arrangement and spacing of the antenna elements [11, 19–21]. For antennas that are spaced half a wavelength apart, a uniform angular power spectrum (i.e., Jakes Model [22, 23]) leads approximately to a decorrelation of incident signals. A smaller angular spread of the channel leads to an increase in correlation.

In order to overcome correlation, accurate spatial models are required. It means we need to model and characterize the radio mobile channel, accurately, to find the exact angular spreads of multipath signals at the BS. These angular spreads can thus be used to find the exact separation between the antenna elements of MIMO arrays. Another fading effect which significantly degrades the performance of a wireless communication and hence the capacity, is the Doppler effect. In fast fading channels, frequency dispersion occurs, which leads to severe signal distortion. Spatial models can also help in modeling the channel correlation coefficients which can later be used in designing fast fading channel estimators.

As far as spatial channel models are concerned, many approaches [2, 3, 24–28] are used to
1.6 Problem Formulation

model the scatterers in some arbitrary scattering region. These approaches are specific either
to the cellular environment or to the distribution of scatterers. However, no generalized
approach for spatial channel modeling has been presented so far. A generalized spatial
channel modeling approach will certainly lead to the accurate characterization of the channel
in angular and temporal domains.

Another important issue, which has not been addressed well in the literature, is the
generalization of the angular spread measure. Several definitions of angular spread [29–33],
have currently being used in the literature, but none is able to attain unanimous acceptance
in the research community. This situation makes the task of performance comparison of
different detection techniques difficult and even leads to wrongful results in some cases.
Since angular spread is the main cause of correlation between antenna elements, its wrong
definition will result in mismatched separations between antenna elements, decreasing the
capacity of the communication system.

All the above issues of performance degradation and capacity reduction are properly
addressed in their respective chapters in the thesis, where detailed overviews and broad
historical backgrounds present a comprehensive picture of our motivations and work.
1.7 Scope of the Thesis and Proposed Methodology

Our methodology to achieve the goals set in the previous section is illustrated in Fig. 1.5. In the first round of our research, we extensively study the previous spatial channel models and find that almost all models are very specific to the particular cellular environments and cannot be generalized. We thus propose a novel spatial channel model, which can be exploited to model any cellular environment with the use of appropriate parameters. In the second round, we derive the angular and temporal statistics of the cellular mobile channel and discuss the impact of local-to-BS scattering on the angular dispersion. In the third round, we address the issue of unanimous definition for the angular spread and propose a novel method of quantifying the angular spread. In the fourth round, we investigate the effect of mobile motion on the spatial and temporal characteristics of the cellular mobile channel, which can lead to the optimization of spatial and temporal statistical parameters as functions of BS-MS separation. In the fifth and last round, we propose a single user adaptive receiver structure for single-carrier DS-CDMA system over time-varying fast fading channel.

Since the modeling approach used in the thesis can easily be extended to address various issues of capacity maximization and performance improvement of a cellular mobile communication system, there are several topics of future research work that can be investigated. For example, the spatial statistics at BS derived in the thesis, can be utilized for the derivation of signal correlations between antenna elements to maximize the capacity of the system. Similarly, robust channel equalizers and RAKE receivers can be designed with the help of
1.7 Scope of the Thesis and Proposed Methodology

Geometrically based Spatial Channel Modeling for all Cellular Environments

Temporal Statistics (pdf of ToA)

Spatial Statistics (pdf of AoA)

Mobile Movement

Doppler Spread

At MS

At BS

Parameters of Delay Spread

Autocorrelation of Time-Varying Channel

Angular Spread at BS Antenna

Coherence Time

Channel Estimator or Channel Tracker

Signal Correlations b/w Antenna Elements

Antenna Diversity

Coherence Distance

Exact Separations b/w Antenna Elements

Channel Equalizer

Rake Receiver

CDMA case

Envelope Fading Compensation

ISI-free Signal Detection

Full Exploitation of Multipath Power in case of CDMA

Signal Detection over Time-Varying Fading Channels in the presence of ISI + Maximum Achievable Capacity by using MIMO multi-antenna system

Figure 1.5: Illustration of the Proposed Dissertation Methodology
temporal statistics, derived in the thesis, for signal detection schemes in frequency selective fading channels. Thus, in order to complete the picture of a full-bodied, efficient and high-capacity cellular mobile communication system, Fig. 1.5 provides all necessary links to various areas of future work, where our proposed results can be exploited.

1.8 Contributions of the Thesis

Following the methodology depicted in Fig. 1.5, we have presented most of our theoretical and practical findings in various international journals and conferences, at different stages of our research tenure. The papers listed under the title of ‘Related Publications’ show such presentations. This dissertation thus presents the systematized and combined version of all those papers. However, some important additions have made it more vigorous and comprehensive.

The organization of the rest of the thesis is as follows:

In Chapter 2, we address the issue of physical channel modeling for the cellular mobile communication system. In the first part of the chapter, we extensively study the previous approaches used for mobile channel modeling in picocell, microcell, and macrocell environments, and present necessary channel modeling parameters. In the second part, we propose a generalized physical channel model, referred to as the ‘Eccentro-Scattering Model’ which can be applied to any type of cellular environment with appropriate choice of eccentricity,
1.8 Contributions of the Thesis

semi-major axis, and distribution of scatterers around MS and/or BS. We also introduce a more applicable scattering model, the Jointly Gaussian Scattering Model (JGSM), which consists of two Gaussian functions each for the distribution of scatterers around BS and MS. We exploit these models (either individually or jointly) later in the thesis, in order to derive the spatial and temporal characteristics of the cellular mobile channel.

In Chapter 3, we exploit the proposed Eccentro-Scattering Model to derive the general expressions for the pdf of AoA of the multipath signals at BS in closed form for picocell, microcell, and macrocell environments, assuming uniform and Gaussian distributed scatterers. Gaussian distributed scatterers are confined, for the first time, within a scattering disc and the advantages of this technique are discussed. Also, distant scatterers are considered in macrocell environments and the pdf of AoA of the multipaths at BS due to dominant distant scattering clusters is derived thereby. Since the AoA statistics are usually affected by the high-rise scattering structures around BS antenna in urban macrocell environments, we propose a modified JGSM model for such environments and present the comparison of its results with the field measurements. The terrain and clutter conditions of the BS surroundings are simply modeled by a scattering-free region around BS. In this way, the radius of the scattering-free region indicates the extent of the density of the scattering structures around BS. All presented formulas are compared with the results obtained by the previous researchers [2,3,24,26–28]. We show that the Eccentro-Scattering model can be used to model any type of cellular environment, by simply changing some of the modeling parameters. A table of comparisons is presented which shows the generality of our proposed
1.8 Contributions of the Thesis

Eccentro-Scattering model.

In Chapter 4, we discuss all previous definitions of the angle spread and propose a novel generalized method of quantifying the angle spread of the multipath power. Our method provides almost all parameters of the dispersion of multipath power in space, which can be further used for calculating more accurate spatial correlations and other statistics of multipath fading channels. These proposed parameters are also helpful in finding the exact standard deviation of truncated or distorted angular distributions as well as of the angular data acquired in measurement campaigns. The resulting standard deviations can lead to the computation of the exact separation distances among array elements needed for the maximization of capacity and the usage of diversity antennas. Keeping the recent use of truncated Gaussian and Laplacian functions as the distributions of AoA in view, we indicate the severity of the effects of distribution truncation on the angle spread. We itemize all those factors which cause such truncations in the AoA distributions and provide analytical solution to compensate for their effects. Furthermore, we propose the angle spread as the goodness-of-fit measure in measurement campaigns and show the comparisons of some notable azimuthal models with the measurement results.

In Chapter 5, we derive simplified closed-form expressions for the ToA distributions for picocell/microcell and macrocell environments by considering the scatterers confined in Eccentro-Scattering discs. This is a more general approach from which the results of the previous models, such as GBSBM model [3], can be deduced as its special cases. For macro-
1.8 Contributions of the Thesis

cell environments, we also include the effect of dominant distant scatterers on the temporal
dispersion of the multipath signals. Objects such as hills, mountains, and skyscrapers act as
clustered scatterers/reflectors when they have line of sight (LoS) to both BS and MS [16, 25].
The derived formulas in chapter 5, can easily be used to simulate temporal dispersion of wire-
less signal in several propagation conditions. Besides the handy use of the pdf of ToA in
determining the coherence bandwidth of a particular system, the pdf of ToA also emerges
as a basic characteristic of the system capacity along with the pdf of AoA [22]. Almost
complete description of the wireless system can be achieved if the pdfs of time and angle of
arrival are known.

In Chapter 6, we consider a realistic situation of a moving MS for the characterization
of multipath fading channel and investigate how this motion affects the spatio-temporal
characteristics at BS. We present three mobile motion scenarios that are responsible for the
alterations in the spatio-temporal characteristics and plot the behavior of various spatial and
temporal spread quantifiers during these motion scenarios. We also explain the behavior of
angle spread under the effect of mobile motion, observed in the field measurements [14]. We
show that the model successfully simulates the time-variability of the angle and delay spreads
induced during the course of MS motion. We identify two different cases when the terrain and
clutter of MS surroundings have an additional effect on the temporal spread of the channel
during MS motion. These cases can provide good basis for the performance evaluation in
those wireless systems which employ additional time-delay processing techniques.
In **Chapter 7**, we develop an autoregressive (AR) model of the time-varying flat fading channel on the basis of its second order fading statistics and utilize it further to establish a linear state-space equation pair for signature sequence adaptation in direct sequence code division multiple access (DS-CDMA) system. We then exploit the Kalman filtering approach to incorporate our proposed state-space equation pair in an algorithm, meant for estimating channel-distorted received signature sequences. It is an established fact [34] that the Kalman filter is a good optimal linear minimum mean squared error (MMSE) detector if a first order linear state-space model is applied to DS-CDMA system. As mentioned earlier, we also use the Kalman filter as the MMSE solution for signature distortions caused by the time-varying fading channel. However, different from the model used in [34], where the unknown transmitted symbol vector has been used as the state-vector, we use channel-distorted received signature vector as the state-vector in our model. This approach is based on the fact that the time-varying channel behaves as the AR model depending on its past values [23, 35]. In our proposed receiver structure, the need for training sequence is bound to the startup period only. Later on, the receiver adapts itself to the changes of the channel during data transmission depending on previous decisions. Simulation results show that being based on the Kalman filter and of non-gradient nature, our proposed algorithm combats effectively the impairments and fading effects caused by time-varying multipath channel.

Finally, **Chapter 8** gives a brief summary of the thesis, discusses the future research work based on the results of the dissertation and presents the concluding remarks.
Chapter 2

A Generalized Spatial Channel Model

This chapter gives a detailed overview of physical spatial channel modeling in its section 2.1. Section 2.2 and 2.3 describe the general channel modeling assumptions and parameters. In section 2.4, the proposed generalized spatial channel model, the *Eccentro-Scattering Model* is presented, which will be used as a global model throughout the thesis. Section 2.5, presents another proposed scattering model, the *Jointly Gaussian Scattering Model* (JGSM), which models the heavy scattering around BS in low antenna-height environments. Section 2.6 discusses the implementation of these models in various cellular environments, discussed in the previous chapter. Finally, section 2.6 gives the summary and final remarks of this chapter.
2.1 Introduction

2.1.1 Overview of Physical Spatial Channel Modeling

With the growing use of antenna arrays in MIMO systems for enhancing system capacity, signal detection, interference cancellation, and position location comes the need to better understand the properties of the spatial channel [36]. MIMO systems have been shown to offer very high information-theoretic capacities [18, 37]. In order to make realistic evaluations of the capabilities of different system architectures and MIMO schemes, realistic channel models are required [38].

Although it is very difficult to categorize the previous approaches used in channel modeling, especially the earlier work [22, 23, 39]; however, Molisch et al. [38] has grouped the recent generic modeling approaches for MIMO channels into the following two categories:

**Non-physical modeling:** This approach is used to model the correlations of the fading of the signals at the antenna elements [40].

**Physical Modeling:** This approach models the location of scatterers/reflectors, or the direction of multipath components at the transmitter and receiver.

The latter approach has become more and more popular recently [38, 41], and is being used in many standard models such as COST 259 DCM [14] and 3GPP [42]. The resultant physical channel models that use physical modeling approach for the location of scatterers/reflectors
are also known as \textit{spatial channel models} or the \textit{scattering models}. Since scatterer locations with respect to MS and BS provide the angular and temporal information of the multi-path signals, the spatial models are very helpful in evaluating the performance of a wireless communication system using antenna arrays.

For spatial models, it is a well-established fact that the scatterer locations (or equivalently, the angles and delays of multipath components) are not distributed uniformly over space, but tend to be concentrated in certain regions [38]. It is possible to obtain the pdf of AoA and power delay profile from the measured data or from site-specific propagation prediction techniques, but this type of data might not always be available. Therefore, physical channel models providing statistics of the channel in angle and time-delay are very helpful in characterizing the angular and time domains of the multipath signals. Accurate and, if possible, simple geometrically-based physical propagation models would lead to an effective design and evaluation of modern communication systems. Such models are low-cost and handy means to accurately predict radio wave propagation behavior.

\subsection*{2.1.2 Previous Work}

Appreciable contributions in spatial channel modeling have been made in [2, 3, 24–28]. The two most common modeling parameters, used by the researchers in spatial channel modeling, involve shape of the scattering region [3, 24–26, 39], and the scatter density in the scattering region [2, 27, 43]. Different shapes of the scattering region were proposed to model the
scattering phenomenon for specific cellular environments. For example, Circular Scattering Model (CSM) was proposed to model the scattering environment in macrocells [3, 25, 26], while Elliptical Scattering Model (ESM) was proposed to model the scattering environments in microcells and picocells [3, 24]. On the other hand, uniform and Gaussian distributions were the most common approaches proposed for the distribution of scatterers within the scattering region. In a uniformly distributed scattering region, scatterers are assumed to have constant density throughout the scattering area, while in a Gaussian distributed scattering region the majority of scattering points are situated close to mobile station (MS) and the density of scattering points decreases as the distance from MS increases. The uniform scattering assumption simplifies the analysis and manipulation whereas the Gaussian distribution is a more realistic approach especially in macrocell environments where no scatterers are assumed around BS, since the scatterers around MS have the greater influence on the received signal as compared to other scatterers [44]. Furthermore, the Gaussian distributed scattering assumption provides higher degrees of freedom to the model in its ability to change the width and density of the scattering area by changing the standard deviation of the distribution of the scatterers around MS.

As far as validity of a model to a particular environment is concerned, the existing models are very specific to the corresponding environments either with respect to the shape of the scattering disc [3, 24–26] or with respect to the standard deviation of the Gaussian distributed scatterers around MS [2, 27]. In [28], an elliptical model was proposed that could be used as a circular one as well, with change in eccentricity of the ellipse assuming
uniformly distributed scattering environment. The model might be suitable for macrocell and quasi-macrocell environments, even though the suitable distribution of the scatterers in macrocells is indeed Gaussian. Nevertheless the model in [28] was not able to explain the radio wave propagation phenomenon in microcell and picocell environments where MS is usually not situated at the center of the scattering area and BS possesses scatterers in addition to those around MS. In such environments the antenna heights, of transmitter and receiver, are relatively low and multipath scattering is assumed near BS to be as likely as that around MS.

The study in [2] proposed a Gaussian Scatter Density Model (GSDM) to be applied to every type of environment by changing only the standard deviation of the scatterers around MS. Generally in picocell environments, scatterers exist in the vicinity of BS as much as around MS. Therefore, it is more practical to model the distribution of scatterers around BS separately from the distribution of scatterers around MS. In other words, a separate Gaussian function for the distribution of scatterers around BS is also needed in addition to the Gaussian function for the distribution of scatterers around MS.

In several measurement campaigns aiming to find the actual distribution of the Angle of Arrival (AoA) of the multipath signals, both in indoor [1, 45–47] and outdoor (microcell [48] and macrocell [4]) environments, different distinct distributions for the AoA of the multipath signals at Base Station (BS) were observed on a short range of angular domain on both sides of the mean AoA, while the distribution over the rest of the angular domain was found to
2.1 Introduction

be very uniform in all cases. Both sides of this uniform region are usually referred to as
the tails of the probability density function (pdf) of AoA. The formation of these uniform
tails in the distribution of AoA remained an unsolved issue in the statistical scattering
models [1, 2, 4] proposed so far. Thus a generalized scattering model is needed which can
explain the formation of these tails in the AoA distribution.

2.1.3 Contributions in the Chapter

In this chapter, we address the issue of physical channel modeling for the cellular mobile com-
munication system. We study intensively the previous approaches used for modeling cellular
mobile channel in picocell, microcell, and macrocell environments. We present necessary
channel modeling parameters and propose a generalized physical channel model, referred to
as the ‘Eccentro-Scattering Model’ which can be applied to any type of cellular environment
with appropriate choice of eccentricity, semi-major axis, and distribution of scatterers around
MS and/or BS. We also introduce a more applicable scattering model, the Jointly Gaussian
Scattering Model (JGSM), which consists of two Gaussian functions each for the distribu-
tion of scatterers around BS and MS. We will exploit these models (either individually or
jointly) to derive the spatial and temporal characteristics of the cellular mobile channel in
the following chapters.
2.2 General Channel Modeling Assumptions

Multiple replicas of the transmitted signal are received at the receiver due to the multipath propagation in the radio environment. These multipath components of the received signal arrive at the receiver antenna from different azimuth directions about the horizon with identical or different delays [22, 23, 49]. The distributions of these multipath components in the azimuth and time are conveniently described by the functions $p(\theta)$ and $p(\tau)$, where $\theta$ is the azimuthal angle of arrival (AoA) [32] and $\tau$ is the delay of the multipath component in time domain. Before proceeding to formulate a generalized spatial channel model, we make the following assumptions:

- Scatterers are confined in an elliptical shaped scattering disc whose eccentricity can be changed according to the maximum delay and the distance between BS and MS. It is
2.2 General Channel Modeling Assumptions

desirable, practically, to consider only those scatterers that have significant influence on the received signal. For example, multipaths with longer delays experience greater path loss and hence have relatively low power as compared to those with shorter delays [24, 44]. In our work, such a scattering disc, which can imitate both circular and elliptical scattering discs with corresponding choice of eccentricity, is referred to as the ‘Eccentro-Scattering Disc’. In the next two sections, we will explain the use of Eccentro-Scattering disc, in detail.

- The received signal at the antenna undergoes no more than one reflection by scatterers when traveling from transmitter to receiver. Placing a scattering object at the last reradiation and approximating the preceding scattering as a stochastic process can retain some of the properties of multiple bounces while providing for a much simpler model [50]. Practically, we are considering only the distribution of scatterers contributing to the last reradiation while the preceding multiple-bounce can be modeled as a stochastic process which has lognormal shadowing with Nakagami fading [20]. This assumption, in conjunction with the first assumption, means that we are considering all scatterers giving rise to a single bounce multipath signal arriving at the receiving antenna before and up to time, $\tau_{\text{max}}$, where $\tau_{\text{max}}$ is the maximum allowed delay, i.e. the time difference between the first and the last signal arrivals at the receiving antenna with signal power greater than some threshold value defined by the system designer.

- Each scatterer is assumed to be an omnidirectional re-radiating element with equal
scattering coefficients and uniform random phases. The word ‘scattering’ is not only used for diffuse scattering but even for those processes that are strictly speaking ‘specular reflections’ [14].

- The effective antenna patterns are omnidirectional for both transmitter and receiver. Practically, the derived formulas for the pdf of AoA should be used in conjunction with the actual antenna radiation pattern.

- BS is set at the origin of the global coordinate system. $\beta$ is the angle between Line of Sight (LoS) and $x$-axis of this coordinate system, see Fig. 2.1. From now onward, the word ‘$x$-axis’ refers to the $x$-axis of the global coordinate system. Hence, the location of any scattering point, $S$, in the system is denoted by the Cartesian coordinates $(x_S, y_S)$ or in polar coordinates $(r_{BS}, \theta)$. Furthermore, the angle $\theta = 0^\circ$ corresponds to the angle towards MS, i.e. the direction of Line of Sight (LoS). Consequently, MS is located at $(x_M, y_M)$ in Cartesian coordinates and at $(d,0)$ in polar coordinates.

- All signals received at the antenna are plane waves coming from the horizon, i.e. only azimuthal coordinates are considered. Some environments such as indoor cellular environments may require knowledge of the elevation angle while in other environments such as macrocell environments the waves propagated over rooftops experience stronger attenuation, therefore, it is reasonable to study only the azimuthal angle in such environments [14]. Yet, the established results are helpful in the analysis and performance assessment of modern wireless techniques, such as smart antenna system, for all cel-
lular environments. The angle $\theta$ in Fig. 2.1 is the azimuthal angle of arrival of the multipath signal at BS with respect to $x$-axis.

- A specific signal delay $\tau$ defines a set of scatterers bounded by an elliptical region, with distinct parameters, which will be referred to as the ‘bounding ellipse’ in our work. The scatterers on the boundary of the bounding ellipse give rise to single bounce multipath components [24, 51]. In chapter 5, we will explain further the significance and usage of the bounding ellipse.

### 2.3 General Channel Modeling Parameters

As discussed earlier in section 2.1 of this chapter, all previous spatial channel models are based on specifying either the shape of the scattering region or the scatterer distribution in the scattering region, in order to model a specific cellular environment.

#### 2.3.1 Shape of the Scattering Region

There are two further models, which are usually used in modeling the scattering environment around MS, depending on the shape of the scattering region with uniform scatter density.
2.3 General Channel Modeling Parameters

Figure 2.2: Modeling with respect to the shape of the scattering region for uniform scatterer distribution

2.3.1.1 Circular Scattering Model

This model is specifically used for macrocell environments [3, 25, 26], where BS antenna is mounted on an elevated place. A typical circular scattering model is shown in Fig. 2.2(a). It can excellently model villages and sparsely populated small towns. Since the distribution of scatterers in macrocell environments tend to be Gaussian, giving rise to Gaussian AoA distribution [4], this model can not be taken as the ultimate solution. However, it is very simple and less calculations are involved in deriving its spatial statistics and correlations among antenna elements at BS. However, the derivation of its temporal characteristics at BS needs complicated calculations.
2.3 General Channel Modeling Parameters

2.3.1.2 Elliptical Scattering Model

This model is specifically used for picocell and microcell environments [3, 24], with low BS antenna heights. A typical elliptical scattering model is shown in Fig. 2.2(b). It can excellently model the indoor propagation phenomenon but fails in modeling dense urban streets, where density of scatterers is not uniform. This model is comparatively more complicated than circular scattering model in deriving its spatial statistics and correlations among antenna elements at BS. However, the derivation of its temporal characteristics is very easy.

2.3.2 Distribution of Scatterers

The wave propagation path changes in different environments according to scatterers’ density and distance between BS and MS in regard to the maximum delay. The two most commonly used approaches in literature for modeling the distribution of scatterers within the scattering disc are the uniform distribution and the Gaussian distribution.

2.3.2.1 Uniformly Distributed Scatterers

A uniform model of the spatial pdf of scatterers distributed uniformly within an arbitrarily shaped region, $R_A$ with an area $A$ around MS (and BS in case of elliptical scattering model) can be written as [3], see Fig. 2.2,

$$p_{x_s,y_s}(x_s, y_s) = \begin{cases} 
\frac{1}{A}, & x_s, y_s \in R_A \\
0, & \text{elsewhere} 
\end{cases} \quad (2.1)$$

41
2.3 General Channel Modeling Parameters

Or in polar coordinates, [52],

\[ p_{R_{BS}, \theta}(r_{BS}, \theta) = \begin{cases} \frac{\|r_{BS}\|}{\Lambda}, & r_{BS} > 0, \quad \{r_{BS}, \theta\} \in R_{A} \\ 0, & \text{elsewhere} \end{cases} \]  

(2.2)

where \( r_{BS} \) is the position vector of the scattering point \( S \) with respect to BS and \( \theta \) is the angle which \( r_{BS} \) makes with the horizontal (in our case the AoA of the multipath signal at BS from scattering point \( S \)), as shown in Fig. 2.2. Also, \( \|x\| \) denotes the norm of any position vector \( x \).

2.3.2.2 Gaussian Distributed Scatterers

The Gaussian distribution of scatterers is a better approximation to physical reality [25]. It assumes that the majority of scattering points are clustered together with their density decreasing as the distance from MS increases [16].

A Gaussian model of the spatial pdf of the scatterers around MS can be written as
2.4 The Proposed Eccentro-Scattering Channel Model

\[ p^{(MS)}_{X_S,Y_S}(x_S,y_S) = \frac{1}{2\pi\sigma_{MS}^2} \exp\left[ -\frac{(x_S-x_M)^2 + (y_S-y_M)^2}{2\sigma_{MS}^2} \right] \quad (2.3) \]

Or in polar coordinates, (2.3) can be written as [52],

\[ p^{(MS)}_{r_{BS},\theta}(r_{BS},\theta) = \begin{cases} \frac{||r_{BS}||}{2\pi\sigma_{MS}^2} \exp\left( -\frac{||r_{BS} - r_{BM}||^2}{2\sigma_{MS}^2} \right), & r_{BS} > 0 \\ 0, & \text{elsewhere} \end{cases} \quad (2.4) \]

where \( \sigma_{MS} \) is the standard deviation of the distribution of scatterers around MS and \( r_{BM} \) is the position vector of MS with respect to BS, as shown in Fig. 2.3. The spatial pdf of the scatterers around MS presented in [25, 27] is deficient in \( r_{BS} \) factor, which is the Jacobian of the transformation from the Cartesian coordinate system to the polar coordinate system.

The so-called Gaussian Scatter Density Model (GSDM) [2] and the other spatial models presented in [27, 43] are based on the Gaussian distribution of scatterers around MS. Although Gaussian distribution is a better approximation to the physical scattering phenomenon, the derivation of spatial statistical formulas in Gaussian distributed scattering is more complicated compared to that in uniform distributed scattering. That is why Gaussian models are not very popular among the research community.

2.4 The Proposed Eccentro-Scattering Channel Model

Consider an ellipse centered at \( C \) with foci \( B \) and \( M \) separated by a distance \( 2f \) and with major and minor axes \( 2a \) and \( 2b \) respectively, as shown in Fig. 2.4. \( r_{BS} \) and \( r_{MS} \) satisfy

\[ r_{BS} + r_{MS} = 2a \quad (2.5) \]
Eccentricity of the ellipse given in Fig. 2.4 is defined as

\[ e = \sqrt{1 - \kappa^2} \]  

where \( \kappa \) (the aspect ratio of the ellipse) = \( b/a \). Eccentricity can also be defined in terms of the distance between the two foci and major axis as

\[ e = \frac{f}{a} \]  

The circle is a special case of the ellipse with \( e = 0 \). The elliptical diagram presented in Fig. 2.4 can easily be implemented to model any cellular mobile environment with scatterers around MS and/or BS.

Restricting the shape of the scattering disc to be either circular or elliptical alone, does not allow full flexibility to the physical channel modeling since the shape of the scattering disc changes in accordance with the terrain, clutter, and location of scattering structures.
2.4 The Proposed Eccentro-Scattering Channel Model

For example, local scatterers in streets and shopping malls in urban areas [44] and dominant distant scatterers like hills near villages and towns in rural areas can be best represented by elliptical scattering discs where the length and width of streets and shopping malls in the case of urban and those of hills in the case of rural areas determine the eccentricities and major axes of the elliptical scattering discs. On the other hand, local scatterers around MS in rural areas are best modeled by circular scattering discs. Therefore, there is a need for a flexible model capable of modeling every type of cellular environment.

In this research work, we exploit the elliptical diagram depicted in Fig. 2.4 to make it feasible to be used as a generalized physical channel model, the ‘Eccentro-Scattering Model’, named due to the fact that it can be applied to any type of cellular environment with appropriate choice of eccentricity, semi-major axis, and distribution of scatterers around MS and/or BS. The elliptical disc of scatterers, whose eccentricity can be adjusted with the type of cellular environment and the conditions of the terrain, is referred to as the ‘Eccentro-Scattering Disc’.

Contrary to the previous physical channel models [2, 3, 24, 26–28], which are very specific to particular environments, the Eccentro-Scattering model provides a unified approach in mobile channel modeling. We will use this model throughout our work for deriving spatial and temporal statistics of the cellular mobile channel.
2.5 The Proposed Jointly Gaussian Scattering (JGSM) Model

As mentioned earlier, Gaussian assumption for the distribution of scatterers in the scattering region is considered the most appropriate in the case of urban, suburban and rural macrocell environments [25]. In these environments, the BS is usually considered free of scatterers. That is why all the previous Gaussian scattering models assume the Gaussian scattering cluster centered at MS. However, in some measurement campaigns aiming to find the actual distribution of the AoA of the multipath signals, both in indoor [1] and outdoor [4] environments, two distinct distributions for the AoA of the multipath signals at BS were observed on a short range of angular domain on both sides of the mean AoA, while the distribution over the rest of the angular domain was found to be very uniform in both cases. Both sides of this uniform region are usually referred to as the tails of the probability density function (pdf) of AoA. The formation of these uniform tails in the distribution of AoA still remains an unsolved issue in the statistical scattering models [1, 2, 4] proposed so far. These tails are in fact the aftermath of the reflections/scattering of the radio signal from the scatterers that surround BS, see Fig. 1.4.

Keeping the effect of scattering in the vicinity of BS in view, we propose a novel Gaussian scattering model for the distribution of scatterers around MS and BS. In our proposed model, Gaussian distributed scattering points around BS are also taken into consideration.
2.5 The Proposed Jointly Gaussian Scattering (JGSM) Model

in addition to Gaussian distributed scattering points around MS in order to simulate real scattering phenomenon more realistically. We propose two distinct Gaussian functions for the distribution of scatterers around BS and MS with different standard deviations. This model will be referred to as the ‘Jointly Gaussian Scattering Model’ (JGSM), in our work. This is in contrast to GSDM, where only one Gaussian function is used for the distribution of scatterers centered at MS. Furthermore, in order to simulate the heaviness of scattering around BS, we introduce a scattering-free zone around BS whose dimensions depend generally on the cell size and BS surroundings. We will explain the significance of this scattering-free region in channel modeling, in the next chapter. Fig. 2.5, depicts JGSM model.

In addition to (2.3), we can write the Gaussian model of the spatial pdf of the scatterers around BS as,

$$p^{(BS)}_{x_S,y_S}(x_S, y_S) = \frac{1}{2\pi\sigma_{BS}^2} \exp \left[ -\frac{x_S^2 + y_S^2}{2\sigma_{BS}^2} \right]$$

(2.8)

Or in polar coordinates, (2.8) can be written as

$$p^{(BS)}_{r_{BS},\theta}(r_{BS}, \theta) = \begin{cases} \frac{\|r_{BS}\|}{2\pi\sigma_{BS}^2} \exp \left( -\frac{\|r_{BS}\|^2}{2\sigma_{BS}^2} \right), & r_{BS} > 0 \\ 0, & \text{elsewhere} \end{cases}$$

(2.9)
2.6 Application of the Eccentro-Scattering Model

where $\sigma_{BS}$ is the standard deviation of the distribution of scatterers around BS. Other notations have been explained in section 2.3.2. JGSM along with the Eccentro-Scattering model provides a generalized approach to characterization of the spatial phenomenon of multipath signals.

2.6 Application of the Eccentro-Scattering Model

We exploit the Eccentro-Scattering model to represent all cellular environments with corresponding choice of eccentricity ($e$), semi-major axis ($a$), and location of the foci and center points of the ellipse.

2.6.1 Picocell Environment

The antenna heights in picocell environments are very low, therefore, the scatterers are assumed to exist near BS as likely as near MS (see Fig. 2.6a). Thus, according to the Eccentro-Scattering model, BS and MS are located at the focal points of the Eccentro-Scattering disc. The choice of the distribution of scatterers depends on the terrain and clutter conditions of the environment. If a shopping mall or railway station is to be modeled, then Gaussian assumption for the distribution of scatterers is the most appropriate choice, otherwise uniform assumption is most suitable for offices and factory halls. In case of Gaussian distributed scatterers, JGSM along with the Eccentro-Scattering model is the best modeling approach.
2.6 Application of the Eccentro-Scattering Model

In the Microcell environment, the antenna heights are also not very high and multipath scattering is usually assumed near BS. However BS possesses relatively few scattering points in its vicinity compared to MS (see Fig. 2.6b). Thus, according to the Eccentro-Scattering model, BS and MS are located at the focal points of the Eccentro-Scattering disc. As for the picocell environment, here also the choice of the distribution of scatterers depends on the terrain and clutter conditions of the environment.

Figure 2.6: Typical (a) Picocell and (b) Microcell Environments in Gaussian distributed scattering

2.6.2 Microcell Environment

In the Microcell environment, the antenna heights are also not very high and multipath scattering is usually assumed near BS. However BS possesses relatively few scattering points in its vicinity compared to MS (see Fig. 2.6b). Thus, according to the Eccentro-Scattering model, BS and MS are located at the focal points of the Eccentro-Scattering disc. As for the picocell environment, here also the choice of the distribution of scatterers depends on the terrain and clutter conditions of the environment.
### 2.6 Application of the Eccentro-Scattering Model

Table 2.1: Typical Values of the Parameters for Pico-cell and Microcell Environments Based on the Eccentro-Scattering Model

<table>
<thead>
<tr>
<th>Environment</th>
<th>Picocell</th>
<th>Microcell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay Spread ($\tau_{\text{max}}$), $\mu$s</td>
<td>$\leq 0.1$</td>
<td>0.3</td>
</tr>
<tr>
<td>Angle Spread ($2\theta_{\text{max}}$), degrees</td>
<td>360</td>
<td>120</td>
</tr>
<tr>
<td>Semi-major axis ($a$), m</td>
<td>$15 &lt; a &lt; 65$</td>
<td>$85 &lt; a &lt; 545$</td>
</tr>
<tr>
<td>Rooftop height, m</td>
<td>Not Applicable</td>
<td>15</td>
</tr>
<tr>
<td>BS antenna height, m</td>
<td>2 – 3</td>
<td>3 – 10</td>
</tr>
<tr>
<td>MS antenna height, m</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Distance between BS and MS ($d$), m</td>
<td>$1 &lt; d &lt; 30$</td>
<td>$1.5 &lt; d &lt; 500$</td>
</tr>
<tr>
<td>Eccentricity ($e$)</td>
<td>$0 &lt; e &lt; 1$</td>
<td>$0.33 &lt; e &lt; 1$</td>
</tr>
<tr>
<td>Numbers of scatterers around BS and MS ($N_B, N_M$)</td>
<td>$N_B \approx N_M, N_M &gt;&gt; 1$</td>
<td>$N_B &lt; N_M, N_M &gt;&gt; 1$</td>
</tr>
<tr>
<td>Standard Deviations ($\sigma_{BS}, \sigma_{MS}$) of scatterers around BS and MS</td>
<td>$\sigma_{BS} = \sigma_{MS}$, $\sigma_{BS} \geq \sigma_{MS}$, $ae \leq \sigma_{MS} \leq 2ae$</td>
<td>$0.4ae \leq \sigma_{MS} \leq 0.68ae$</td>
</tr>
</tbody>
</table>
2.6 Application of the Eccentro-Scattering Model

Table 2.2: Typical Values of the Parameters for Macrocell Environments Based on the Eccentro-Scattering Model

<table>
<thead>
<tr>
<th>Environment</th>
<th>Rural</th>
<th>Typical Urban</th>
<th>Suburban or Bad Urban</th>
<th>Hilly</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Local to MS only</td>
<td>Local to MS only</td>
<td>Local to MS</td>
<td>Distant</td>
</tr>
<tr>
<td>Nature of Scatterers</td>
<td>Rural</td>
<td>Typical Urban</td>
<td>Suburban or Bad Urban</td>
<td>Rural</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>Typical Urban</td>
<td>Suburban or Bad Urban</td>
<td>Rural</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>Typical Urban</td>
<td>Suburban or Bad Urban</td>
<td>Rural</td>
</tr>
<tr>
<td>Delay Spread, $\mu$s</td>
<td>0.5</td>
<td>5</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>Angle Spread, degrees</td>
<td>1</td>
<td>20</td>
<td>20 - 25</td>
<td>2</td>
</tr>
<tr>
<td>Rooftop height, $m$</td>
<td>-</td>
<td>15</td>
<td>30</td>
<td>-</td>
</tr>
<tr>
<td>BS antenna height, $m$</td>
<td>50</td>
<td>30</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>MS antenna height, $m$</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Distance between BS and MS, $m$</td>
<td>5000</td>
<td>500</td>
<td>500</td>
<td>-</td>
</tr>
<tr>
<td>Semi-major axis of local scattering disc, $a$, $m$</td>
<td>75</td>
<td>750</td>
<td>75 - 750</td>
<td>-</td>
</tr>
<tr>
<td>Eccentricity of local scattering disc, $e$</td>
<td>0</td>
<td>$\approx$ 0.4</td>
<td>0.2 - 0.4</td>
<td>-</td>
</tr>
<tr>
<td>Distance between BS and MS via center of the distant scattering disc, $D, m$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$D \leq 3000$</td>
</tr>
<tr>
<td>Semi-major axis of distant scattering disc, $a_D, m$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>75 - 750</td>
</tr>
<tr>
<td>Eccentricity of distant scattering disc, $e_D$</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>$\approx$ 0.2</td>
</tr>
</tbody>
</table>
2.6 Application of the Eccentro-Scattering Model

2.6.3 Macrocell Environment

In the macrocell environment, the BS antenna is higher than the surrounding buildings/scatterers, therefore, it is viable to assume no scatterers in the vicinity of BS. Here, the received signal at BS results predominantly from the local scattering process in the vicinity of MS [15] and the distant scattering process in the transmission path between BS and MS. Thus, according to the Eccentro-Scattering model, BS is located outside the scattering region and MS is located at the center of the Eccentro-Scattering disc. We also consider another Eccentro-Scattering disc for the remote scatterers with some arbitrary center, which depends on the geographical terrain conditions of the scattering structures.

We consider suburban and hilly macrocell environments as having both dominant distant scatterers and local scatterers [41] as shown in Fig. 1.4(b), while in flat rural and urban macrocell environments we only consider local scatterers around MS.

Exemplary values of the model parameters are listed in Tables 2.1 and 2.2. The values in the tables are merely typical and they may differ slightly from more specific ones. For example, the delay spread in corridors (picocells) may become larger than what is indicated in Table 2.1. This difference in values usually results from the variety of antennas, measurement techniques, measurement locations, and various assumptions made by the working groups. However, we have chosen the most appropriate values for the model parameters listed in Tables 2.1 and 2.2 from the studies in [2, 11, 14, 16, 53].
2.7 Summary of the Chapter

In this chapter, we have addressed the issue of physical channel modeling for the cellular mobile communication system. We have studied intensively the previous approaches used for modeling cellular mobile channel in picocell, microcell, and macrocell environments. We have developed necessary channel modeling parameters and proposed a generalized physical channel model, referred to as the ‘Eccentro-Scattering Model’, which can be applied to any type of cellular environment with appropriate choice of eccentricity, semi-major axis, and distribution of scatterers around MS and/or BS. We have also introduced a more applicable scattering model, the Jointly Gaussian Scattering Model (JGSM), which consists of two Gaussian functions each for the distribution of scatterers around BS and MS. We will exploit both the JGSM and the Eccentro-Scattering model (either individually or jointly) to derive the spatial and temporal characteristics of the cellular mobile channel in the following chapters. The same methodology can also be used to develop a spatial channel model for a 3-D environment.
Chapter 3

Modeling Spatial Characteristics of Mobile Channel

In this chapter, section 3.1 gives overview of the chapter contributions. Section 3.2 and 3.3 present the derivation of the closed-form formulas for the pdf in AoA of multipaths as seen from BS for picocell/microcell and macrocell environments. Section 3.4 models the impact of scattering around BS on the AoA statistics of the cellular mobile channel in dense urban environments. Finally, section 3.5 concludes the paper and presents final remarks.
3.1 Overview

In this chapter, we exploit the proposed Eccentro-Scattering Model to derive the general expressions for the pdf of AoA of the multipaths at BS in closed form for picocell, microcell, and macrocell environments assuming uniform and Gaussian distributed scatterers. Gaussian distributed scatterers are confined, for the first time, within a scattering disc and the advantages of this technique are discussed. Also, distant scatterers are considered in macrocell environments and the pdf of AoA of the multipaths at BS due to dominant distant scattering clusters is derived thereby. Since the AoA statistics are usually affected by the high-rise scattering structures around BS antenna in urban macrocell environments, we propose a modified JGSM model for such environments and present its comparison with the field measurements. The terrain and clutter conditions of the BS surroundings are simply modeled by a scattering-free region around BS. In this way, the radius of the scattering-free region indicates the extent of the density of the scattering structures around BS. All presented formulas are compared with the results obtained by the previous researchers [2, 3, 24, 26–28]. We show that the Eccentro-Scattering model can be used to model any type of cellular environment, by simply changing some of the modeling parameters. A table of comparisons is presented which shows the generality of the Eccentro-Scattering model, proposed in the previous chapter.
3.2 Angle Of Arrival For Picocell And Microcell Environments

In picocell and microcell environments, both MS and BS are considered to have local scatterers in their vicinity [41, 44] as shown in Fig. 2.6. The scatterers are confined in an Eccentro-Scattering disc whose eccentricity can be changed according to the distance between BS and MS and the maximum delay. Table 2.1 provides the corresponding choice of parameters. Using radio signal propagation theory, the relationship among maximum delay $\tau_{\text{max}}$, total path travelled $r_{BS} + r_{MS}$, and speed of light $c$ can be written as,

$$r_{BS} + r_{MS} = c\tau_{\text{max}}$$  \hspace{1cm} (3.1)

The propagated radio signal experiences shorter delays in picocell and microcell environments as compared to macrocell environment. Criteria for selecting $\tau_{\text{max}}$ can be found in [24]. From (2.5) and (3.1), the semi-major axis of the ellipse is,

$$a = \frac{c\tau_{\text{max}}}{2}$$  \hspace{1cm} (3.2)

Here, the distance between BS and MS, $d$, is equal to $2f$, so using (2.6) and (2.7), the semi-minor axis $b$ and eccentricity $e$ of the Eccentro-Scattering discs in Fig. 3.1(a) and Fig. 3.2(a) can be written, respectively, as,

$$b = \frac{1}{2} \sqrt{4a^2 - d^2}$$  \hspace{1cm} (3.3)

$$e = \frac{d}{2a}$$  \hspace{1cm} (3.4)
Figure 3.1: Eccentro-Scattering model in uniform scattering
3.2 Angle Of Arrival For Picocell And Microcell Environments

The area bounded by the sector $BSQ$ in Fig. 3.1(a) and Fig. 3.2(a) is a function of the angle $\theta$, with angles between $0^\circ$ and $\theta_{max}$. For picocells, the maximum AoA, $\theta_{max}$ is $180^\circ$ [53], which means multipath signals are arriving at BS antenna from all directions, whereas in microcells, it was found that most of the multipath signals have maximum AoA, $\theta_{max}$ of $60^\circ$ [53]. The distance between BS and MS, $d$, is larger in the case of microcell environment as compared to that in the case of picocell environment.

3.2.1 Uniformly Distributed Scatterers

Fig. 3.1(a) represents the Eccentro-Scattering model for uniformly distributed scatterers in picocells and microcells. Considering (2.2) and the geometry in Fig. 3.1(a), the Cumulative Distribution Function (CDF) of the scattering points around BS and MS would be,

$$P_\Theta(\theta) = \int_{-\theta_{max}}^{\theta} \int_0^{z_2} \frac{r_{BS}}{A_e} dr_{BS} d\zeta = \int_{-\theta_{max}}^{\theta} \frac{z_2(\zeta)}{2A_e} d\zeta$$

(3.5)

where $A_e$ is the area of the ellipse, $\zeta$ is a dummy variable used for the AoA and $z_2$ is the positive root of the equation defining the ellipse of Fig. 3.1(a) in polar coordinates,

$$r_{BS}^2 \left( \frac{\cos^2 \theta}{a^2} + \frac{\sin^2 \theta}{b^2} \right) - r_{BS} \left( \frac{d \cos \theta}{a^2} \right) + \frac{d^2}{4a^2} - 1 = 0$$

(3.6)

Solving for $r_{BS}$ results in the following two solutions,

$$z_1(\theta), z_2(\theta) = \frac{4a^2 - d^2}{2(\pm 2a - d \cos \theta)}$$

(3.7)
3.2 Angle Of Arrival For Picocell And Microcell Environments

So the pdf of AoA of the multipaths from all scattering points within the Eccentro-Scattering disc, \( p_\theta(\theta) \), would be the derivative of (3.5) with respect to \( \theta \),

\[
p_\theta(\theta) = \frac{d}{d\theta} P_\theta(\theta) = \frac{z^2_2(\theta)}{2A_e}
\]  (3.8)

Since \( A_e = \frac{\pi a^2}{2} \sqrt{4a^2 - d^2} \), therefore,

\[
p_\theta(\theta) = \frac{(4a^2 - d^2)^{3/2}}{4\pi a (2a - d \cos \theta)^2}
\]  (3.9)

Introducing eccentricity into (3.9), we get,

\[
p_\theta(\theta) = \frac{(1 - e^2)^{3/2}}{2\pi (1 - e \cos \theta)^2}
\]  (3.10)

It is evident from (3.10) that the pdf of AoA of the multipaths from all scattering points within the Eccentro-Scattering disc depends mainly on its eccentricity. In other words, the pdf of AoA of the multipaths at BS in picocell and microcell environments is primarily determined by the ratio of BS-MS distance to the major axis of the Eccentro-Scattering disc.

3.2.2 Gaussian Distributed Scatterers

Practically speaking, in picocells, the density of scatterers around MS is almost equal to that around BS due to having the same scattering environment around their antennas, whereas in microcells, the density of scatterers around MS is greater than that around BS.

Previously, researchers [2, 27] derived the pdf formulas assuming unbounded Gaussian scattering points centered at MS. Even though this assumption simplifies the derivation, it
3.2 Angle Of Arrival For Picocell And Microcell Environments

Figure 3.2: Eccentro-Scattering model in Gaussian scattering
is impractical because the maximum delay $\tau_{\text{max}}$ specifies nearly all the power and AoA of the multipath signals within some region. Hence, multipaths with longer delays experience greater path loss and, therefore, have relatively low power compared to those with shorter delays [16, 24]. It is more realistic to confine the scatterers inside a scattering disc as proposed in Eccentro-Scattering model. Since the scattering points local to BS have a significant effect on the AoA statistics, it is more viable to use the JGSM discussed earlier. That is why we are considering two separate Gaussian functions for the distribution of scatterers around BS and MS.

Considering (2.4) and the geometry in Fig. 3.2(a), the density of the scattering points around MS can be described by the bivariate Gaussian distribution,

$$p^{(MS)}_{R_{BS},\theta}(r_{BS}, \theta) = \begin{cases} \frac{r_{BS}}{2\pi \sigma_{MS}^2} \exp \left( -\frac{r_{BS}^2 + d^2 - 2r_{BS}d \cos \theta}{2\sigma_{MS}^2} \right), & r_{BS} > 0 \\ 0, & \text{elsewhere} \end{cases}$$

(3.11)

where $\theta$ is the AoA at BS measured from the horizontal.

In a similar way, considering (2.9) and the geometry in Fig. 3.2(a), the density of the scattering points around BS can be found as,

$$p^{(BS)}_{R_{BS},\theta}(r_{BS}, \theta) = \begin{cases} \frac{r_{BS}}{2\pi \sigma_{BS}^2} \exp \left( -\frac{r_{BS}^2}{2\sigma_{BS}^2} \right), & r_{BS} > 0 \\ 0, & \text{elsewhere} \end{cases}$$

(3.12)

Considering (3.11) and (3.12) and the geometry in Fig. 3.2(a), the CDF of the scattering points around MS and BS would be, respectively,
\[ P_{\Theta}^{(MS)}(\theta) = \int_{-\theta_{\text{max}}}^{\theta} \int_{0}^{z_2} \frac{r_{BS}}{2\pi \sigma_{MS}^2} \exp\left( -\frac{r_{BS}^2 - d^2 + 2r_{BS}d \cos \zeta}{2\sigma_{MS}^2} \right) dr_{BS} d\zeta \] (3.13)

and

\[ P_{\Theta}^{(BS)}(\theta) = \int_{-\theta_{\text{max}}}^{\theta} \int_{0}^{z_2} \frac{r_{BS}}{2\pi \sigma_{BS}^2} \exp\left( -\frac{r_{BS}^2}{2\sigma_{BS}^2} \right) dr_{BS} d\zeta \] (3.14)

where \( z_2 \) is the positive root of the equation defining the ellipse of Fig. 3.2(a) and is defined in (3.7). Since the received signal at the antenna has interacted with only one single scatterer in the channel, as assumed earlier, then the AoA of the multipaths from scatterers around BS and MS are two disjoint events. Hence, the pdf of AoA of the multipaths from all scattering points within the Eccentro-Scattering disc, \( p_{\Theta}(\theta) \), would be basically the addition of the derivatives of (3.13) and (3.14) with respect to \( \theta \),

\[ p_{\Theta}(\theta) = \frac{1}{2} \left( p_{\Theta}^{(MS)}(\theta) + p_{\Theta}^{(BS)}(\theta) \right) = \frac{1}{2} \left( \frac{d}{d\theta} P_{\Theta}^{(MS)}(\theta) + \frac{d}{d\theta} P_{\Theta}^{(BS)}(\theta) \right) \] (3.15)

therefore,

\[ p_{\Theta}(\theta) = \int_{0}^{z_2} \frac{r_{BS}}{2\pi \sigma_{MS}^2} \exp\left( -\frac{r_{BS}^2 - d^2 + 2r_{BS}d \cos \theta}{2\sigma_{MS}^2} \right) dr_{BS} + \int_{0}^{z_2} \frac{r_{BS}}{2\pi \sigma_{BS}^2} \exp\left( -\frac{r_{BS}^2}{2\sigma_{BS}^2} \right) dr_{BS} \] (3.16)

Substituting the values of \( z_2 \) from (3.7) into (3.16), we get the pdf of AoA of the multipaths at BS from Gaussian distributed scatterers around BS and MS confined within...
3.2 Angle Of Arrival For Picocell And Microcell Environments

\begin{align*}
\text{Figure 3.3: Effect of increasing } a \text{ with respect to } \sigma_{MS} \text{ on the pdf of AoA in picocells and microcells, } \\
\sigma_{BS}=0.
\end{align*}

the Eccentro-Scattering disc as,

\begin{align*}
p_{\theta}(\theta) &= \frac{\Omega}{4\pi} \left[ 1 + \exp \left( - \frac{d^2}{2\sigma_{MS}^2} \right) - \exp \left( - \frac{(4a^2 - 4ad \cos \theta + d^2)^2}{8\sigma_{MS}^2(2a - d \cos \theta)^2} \right) \\
&\quad + \frac{\sqrt{\pi}d \cos \theta}{\sqrt{2}\sigma_{MS}} \exp \left( - \frac{d^2 \sin^2 \theta}{2\sigma_{MS}^2} \right) \left\{ \text{erf} \left( \frac{d \cos \theta}{\sqrt{2}\sigma_{MS}} \right) + \text{erf} \left( \frac{4a^2 - 4ad \cos \theta + d^2 \cos 2\theta}{2\sqrt{2}\sigma_{MS}(2a - d \cos \theta)} \right) \right\} \\
&\quad - \exp \left( - \frac{(4a^2 - d^2)^2}{8\sigma_{BS}^2(2a - d \cos \theta)^2} \right) \right] \tag{3.17}
\end{align*}

where \(\Omega\) is the normalizing constant such that \(\int_{0}^{2\pi} p_{\theta}(\theta) d\theta = 1\), and \(\text{erf}(x)\) is the well known error function defined as: \(\text{erf}(x) = \int_{0}^{x} \exp(-t^2) dt\).

The following remarks can be made about (3.17):

63
3.2 Angle Of Arrival For Picocell And Microcell Environments

1. If we consider \( \sigma_{MS} = \infty \) and \( \sigma_{BS} = 0 \), (3.17) approaches a uniform distribution for the AoA of the multipaths at BS.

2. If we consider \( a = 4\sigma_{MS} \) and \( \sigma_{BS} = 0 \), (3.17) approaches the result found by Janaswamy [2] for unbounded Gaussian distributed scatterers around MS only. This result implies because, at \( a = 4\sigma_{MS} \), the Eccentro-Scattering disc would confine almost all (99.99%) of the scattering points. Whereas, practically, \( a \) must be smaller than \( 4\sigma_{MS} \). In Fig. 3.3, we observe that when \( a \) is increased, the pdf of AoA curve tends to overlap the corresponding curve obtained in case of unbounded scatterers [2]. At \( a = 4\sigma_{MS} \), the exact overlap occurs, and the effect of increasing \( a \) on the pdf of AoA curve stops for all values of \( a \) greater than \( 4\sigma_{MS} \). In other words, we can say that the pdf of AoA of the multipaths at BS depends on the value of \( a \) such that \( a \leq 4\sigma_{MS} \). Therefore it is more realistic to bound the scatterers inside some scattering disc according to terrain conditions, i.e. in an Eccentro-Scattering disc.

3. If we consider \( \sigma_{MS} \geq 3a \) and \( \sigma_{BS} = 0 \), (3.17) approaches the results found originally by Liberti [24] and derived again in a compact form by Ertel [3] for bounded uniformly distributed scatterers confined in an elliptical scattering disc. Fig. 3.4 shows the effect of using large values for \( \sigma_{MS} \) on the pdf of AoA of the multipaths at BS. The pdf of AoA curves are plotted for different values of \( \sigma_{MS} \). For the sake of convenience, the values of \( \sigma_{MS} \) are given in terms of \( a \). We observe that as we increase \( \sigma_{MS} \), the pdf of AoA curve tends to overlap the curve obtained in case of uniformly distributed
3.2 Angle Of Arrival For Picocell And Microcell Environments

Figure 3.4: Effect of increasing $\sigma_{MS}$ with respect to $a$ on the pdf of AoA in picocells and microcells, $\sigma_{BS}=0$.

scatterers bounded in an elliptical disc [3]. We thus conclude that Gaussian distributed scatterers confined in an Eccentro-Scattering disc with large values of $\sigma_{MS}$ show the same results as uniformly distributed scatterers confined within the disc.

These results illustrate the generality of the Eccentro-Scattering model.

In picocell or indoor environments, the effect of standard deviation of the scatterers is not so visible because BS and MS are usually located very close to each other, while in microcell environment this effect is more obvious because BS and MS are relatively far from each other and the scattering disc gets larger values of eccentricity, $e$ (closer to 1).
3.2 Angle Of Arrival For Picocell And Microcell Environments

Figure 3.5: Comparison of the pdf in AoA for the Eccentro-Scattering model, and Laplacian function with measurements [1].

In the indoor measurement campaigns [1, 45–47], the formation of tails in the pdf of AoA curves is actually due to the scattering effect of the radio waves by the scatterers closer to BS. This phenomenon strengthens the assumption of additional Gaussian distributed scatterers around BS. Fig. 3.5 shows the comparison of the Eccentro-Scattering model with the field measurements obtained by Spencer [1]. The pdf of AoA curves using the Eccentro-Scattering model and Laplacian function (suggested by [1]) are plotted against measurement data on logarithmic scale. Eccentro-Scattering model shows the best fit for the data, especially for the tails of the distribution. The tails of the other measurements can also be dealt with using the same approach.
3.3 Angle Of Arrival For Macrocell Environment

Usually in picocell environment, the curve of the azimuthal distribution of AoA at BS is same as that at MS in shape. However, this phenomenon slightly differs in microcell urban environments, where streets behave as wave-guides giving different shape to the azimuthal distribution at MS. Anyhow, the azimuthal distribution of AoA at BS retains its common shape, i.e. sharp rise on both sides of the mean AoA along LOS and uniform tails on the rest of the domain. In [48], 3-D high-resolution AoA distribution plots have been presented for different urban scenarios which reveal the formation of tails in their azimuthal domain in most of the cases depending on the orientation of the streets. The Eccentro-Scattering model provides the best modeling approach to represent widths and lengths of the streets in microcells with the help of corresponding change in the eccentricity $e$.

3.3 Angle Of Arrival For Macrocell Environment

In this section, we derive the pdf of AoA of the multipaths at BS for macrocell environments. As mentioned earlier, BS is at a large distance from MS in macrocell environments and no scattering is assumed in its vicinity. Further, we consider distant scattering discs in hilly and suburban areas to represent large scattering structures such as mountains and high rise building clusters.

Fig. 3.1(b) and Fig. 3.2(b) are modified representations of the Eccentro-Scattering model for macrocell environment, in uniformly and Gaussian distributed scattering regions respec-
3.3 Angle Of Arrival For Macrocell Environment

Figure 3.6: Typical macrocell environment

Consider the ellipses centered at $M$ (MS) with semi-major and semi-minor axes $a$ and $b$, respectively, as given in Fig. 3.1(b) and Fig. 3.2(b). $d$ is the distance between $B$ (BS) and $M$ (MS) and $S$ is a scattering point in the vicinity of MS. $\theta$ is the angle between the position vector of any scattering point and x-axis, i.e. the AoA of the multipaths at BS, taking values between $-\theta_{L,\text{max}}$ and $\theta_{L,\text{max}}$, where $\theta_{L,\text{max}}$ is the maximum AoA at BS in local Eccentro-Scattering case defined as,

$$\theta_{L,\text{max}} = \arctan\left(\kappa \tan\left(\arcsin\left(\frac{a}{d}\right)\right)\right)$$

(3.18)

where $\kappa$ (the aspect ratio of the local Eccentro-Scattering disc) = $b/a$.

In macrocells, the eccentricity of the local Eccentro-Scattering disc does not depend on $d$, because BS is located outside the scattering region, however it depends on the terrain and clutter of the scattering environment.

Likewise for the distant Eccentro-Scattering disc, $a_D$ and $b_D$ are the semi-major and
3.3 Angle Of Arrival For Macrocell Environment

semi-minor axes of the distant Eccentro-Scattering disc, \( P \) is a scattering point in that disc, \( D \) is the total distance between BS and MS via \( C_D \), the center of the distant scattering disc, i.e., \( D = \| r_{BC_D} \| + \| r_{MC_D} \| \) where \( \| r_{BC_D} \| \) and \( \| r_{MC_D} \| \) are shown in Fig. 3.1(b) and Fig. 3.2(b). \( d_D \) is the distance between BS and \( C_D \), i.e., \( d_D = \| r_{BC_D} \| \), \( \theta_D \) is the angle of \( \| r_{BC_D} \| \) with x-axis. We assume the major axis of the distant Eccentro-Scattering disc is parallel to \( r_{BC_D} \). This assumption is just for the sake of making the modeling easy, otherwise any orientation of the distant Eccentro-Scattering disc can be taken according to the physical location of distant scattering structures. For the distant scattering points, \( \theta \) takes values between \( \theta_D - \theta_{D,\text{max}} \) and \( \theta_D + \theta_{D,\text{max}} \), where \( \theta_{D,\text{max}} \) is the maximum AoA for distant Eccentro-Scattering case defined as,

\[
\theta_{D,\text{max}} = \arctan \left( \kappa_D \tan \left( \arcsin \left( \frac{a_D}{d_D} \right) \right) \right)
\]

where \( \kappa_D \) (the aspect ratio of the distant Eccentro-Scattering disc) = \( b_D/a_D \). From the geometry of Fig. 3.1(b) and Fig. 3.2(b), the angular spread, \( 2\theta_{\text{max}} \), is defined as,

\[
2\theta_{\text{max}} = \theta_{L,\text{max}} + \theta_{D,\text{max}} + \theta_D
\]

In the case of using two directional antennas to illuminate both local and distant scatterers, \( 2\theta_{L,\text{max}} \) and \( 2\theta_{D,\text{max}} \) would be treated as separate angular spreads each for individual antenna as shown in Fig. 3.6.

In Fig. 3.1(b) and Fig. 3.2(b), where a dominant distant Eccentro-Scattering disc exists in addition to the local Eccentro-Scattering disc, the area bounded by the sector \( GJSH \) in
the local Eccentro-Scattering disc is a function of the angle \(\theta\), with angles between 0 and \(\theta_{L,\text{max}}\), and the area bounded by the sector \(UQPV\) in the distant Eccentro-Scattering disc is a function of the angle \(\theta\), with angles between \(\theta_D\) and \(\theta_D + \theta_{D,\text{max}}\). Table 2.2 specifies the choice of the Eccentro-Scattering model parameters for macrocell environment in detail.

### 3.3.1 Uniformly Distributed Scatterers

Considering (2.2) and the geometry in Fig. 3.1(b), the CDFs of the scattering points for the local and distant Eccentro-Scattering discs will be, respectively,

\[
P^{(L)}(\theta) = \int_{\theta_{L,\text{max}}}^{\theta} \int_{z_1}^{z_2} \frac{r_{BS}}{A_L} \, dr_{BS} \, d\zeta = \int_{\theta_{L,\text{max}}}^{\theta} \frac{z_2^2(\zeta) - z_1^2(\zeta)}{2A_L} \, d\zeta \tag{3.21}
\]

and

\[
P^{(D)}(\theta) = \int_{\theta_D - \theta_{D,\text{max}}}^{\theta_D + \theta} \int_{w_1}^{w_2} \frac{r_{BP}}{A_D} \, dr_{BP} \, d\zeta = \int_{\theta_D - \theta_{D,\text{max}}}^{\theta_D + \theta} \frac{w_2^2(\zeta) - w_1^2(\zeta)}{2A_D} \, d\zeta \tag{3.22}
\]

where \(A_L = \pi ab\), \(A_D = \pi a_D b_D\), and \(z_1, z_2, w_1, w_2\) are two pairs of roots for the equations defining the local and distant Eccentro-Scattering discs, respectively, in polar coordinates,

\[
r_{BS}^2 \left( \frac{\cos^2 \theta}{a^2} + \frac{\sin^2 \theta}{b^2} \right) - r_{BS} \left( \frac{2d \cos \theta}{a^2} \right) + \frac{d^2}{a^2} - 1 = 0 \tag{3.23}
\]

and

\[
r_{BP}^2 \left( \frac{\cos^2 \theta}{a_D^2} + \frac{\sin^2 \theta}{b_D^2} \right) - 2d_D r_{BP} \left( \frac{\cos \theta \cos \theta_D}{a_D^2} + \frac{\sin \theta \sin \theta_D}{b_D^2} \right) + \frac{d_D^2}{a_D^2} \left( \frac{\cos^2 \theta_D}{a_D^2} + \frac{\sin^2 \theta_D}{b_D^2} \right) - 1 = 0 \tag{3.24}
\]

with roots,

\[
z_1, z_2 = \frac{b^2 d \cos \theta \pm \sqrt{a^2 \sin^2 \theta + b^2 \cos^2 \theta - d^2 \sin^2 \theta}}{a^2 \sin^2 \theta + b^2 \cos^2 \theta} \tag{3.25}
\]
3.3 Angle Of Arrival For Macrocell Environment

and

\[
w_1, w_2 = \frac{d_D (a_D^2 \sin \theta \sin \theta_D + b_D^2 \cos \theta \cos \theta_D) \pm a_D b_D \sqrt{a_D^2 \sin^2 \theta + b_D^2 \cos^2 \theta - d_D^2 \sin^2 (\theta - \theta_D)}}{a_D^2 \sin^2 \theta + b_D^2 \cos^2 \theta}
\]

(3.26)

The above-mentioned quantities are \( z_1 = |BJ|, z_2 = |BS|, w_1 = |BQ| \) and \( w_2 = |BP| \) as shown in Fig. 3.1(b).

Substituting the values of \( z_1, z_2 \) and \( w_1, w_2 \) from (3.25) and (3.26) into (3.21) and (3.22) and differentiating with respect to \( \theta \), we get the pdf of AoA of the multipaths at BS from the scatterers confined in the local and distant Eccentro-Scattering discs as follows,

\[
p_\Theta(\theta) = \begin{cases} 
2\kappa^2 E \cos \theta \sqrt{\sin^2 \theta + \kappa^2 \cos^2 \theta - E^2 \sin^2 \theta} & -\theta_L,\max \leq \theta \leq \theta_L,\max \\
\pi (\sin^2 \theta + \kappa^2 \cos^2 \theta)^2 & \theta_L,\max < \theta < \theta_D - \theta_D,\max \\
0, & \theta_D - \theta_D,\max \leq \theta \leq \theta_D + \theta_D,\max \\
0, & \text{elsewhere}
\end{cases}
\]

(3.27)

where \( E = d/a \) and \( E_D = d_D/a_D \) are important ratios that help in designing directional antennas for local and dominant distant scattering environments especially in urban, suburban, rural, and hilly areas.
3.3 Angle Of Arrival For Macrocell Environment

3.3.2 Gaussian Distributed Scatterers

Once again we say that Gaussian distributed scatterers represent a better assumption to the real situations in macrocell environments. Here also, we confine the Gaussian distributed scatterers, both local and distant, inside the Eccentro-Scattering discs since it is more practical as discussed earlier.

Considering (2.4) and the geometry in Fig. 3.2(b), the CDFs of the scattering points for the local and distant Eccentro-Scattering discs will be, respectively,

$$P^{(L)}_{\Theta}(\theta) = \int_{-\theta_{L,\text{max}}}^{\theta} \int_{z_1}^{z_2} \frac{r_{BS}}{2\pi \sigma^2_{MS}} \exp \left( \frac{-r_{BS}^2 - d^2 + 2r_{BS}d \cos \zeta}{2\sigma^2_{MS}} \right) dr_{BS} d\zeta \quad (3.28)$$

and

$$P^{(D)}_{\Theta}(\theta) = \int_{\theta_{D,\text{max}}}^{\theta + \theta} \int_{w_1}^{w_2} \frac{r_{BP}}{2\pi \sigma^2_D} \exp \left( \frac{-r_{BP}^2 - d^2_D + 2r_{BP}d_D \cos(\zeta - \theta_D)}{2\sigma^2_D} \right) dr_{BP} d\zeta \quad (3.29)$$

where $z_1$, $z_2$ and $w_1$, $w_2$ are as defined in (3.25) and (3.26).

To simplify the derivation, we assume a circular disc for the distant scatterers, i.e. $\kappa_D = 1$, so, substituting $a_D$ and $b_D$ by $R_D$ in (3.24) and solving for $r_{BP}$, results in the following two solutions,

$$w_1, w_2 = d_D \cos(\theta - \theta_D) \mp \sqrt{R_D^2 - d_D^2 \sin^2(\theta - \theta_D)} \quad (3.30)$$

Substituting the values of $z_1$, $z_2$ from (3.25) and $w_1$, $w_2$ from (3.30) into (3.28) and (3.29) and differentiating with respect to $\theta$, we get the pdf of AoA of the multipaths at BS.
from the scatterers confined in the local and distant Eccentro-Scattering discs as follows,

\[
p_\theta (\theta) = \begin{cases} 
  K_1 \exp \left( \frac{-\kappa^2 f_1^2 + 2\kappa f_1 f_2 - E^2 \sin^2 \theta \left( \sin^2 \theta + \kappa^4 \cos^2 \theta \right)}{f_3^2} \right) \left[ \exp \left( \frac{-4\kappa f_1 f_2}{f_3^2} \right) - 1 \right] \\
  + K_2 E \cos \theta \exp \left( -\frac{a^2 E^2 \sin^2 \theta}{2 \sigma_{MS}^2} \right) \left[ \text{erf} \left( \frac{\kappa f_1 + f_2}{f_3} \right) + \text{erf} \left( \frac{\kappa f_1 - f_2}{f_3} \right) \right], \\
  \quad -\theta_{L,\text{max}} \leq \theta \leq \theta_{L,\text{max}} \\
  0, \\
  \quad \theta_{L,\text{max}} < \theta < \theta_D - \theta_{D,\text{max}} \\
  \Omega \frac{R_D \cos(\theta - \theta_D)}{\sqrt{2\pi \sigma_D}} \exp \left( \frac{R_D^2 E_D^2 \sin^2(\theta - \theta_D)}{2 \sigma_D^2} \right) \text{erf} \left( \frac{R_D \sqrt{1 - E_D^2 \sin^2(\theta - \theta_D)}}{\sqrt{2\sigma_D}} \right), \\
  \quad \theta_D - \theta_{D,\text{max}} \leq \theta \leq \theta_D + \theta_{D,\text{max}} \\
  0, \\
  \quad \text{elsewhere}
\end{cases}
\] (3.31)

where \( K_1 = \frac{\Omega}{2\pi} \) and \( K_2 = \frac{\Omega a}{2 \sigma_{MS} \sqrt{2\pi}} \) are constants, \( f_1 = \sqrt{\sin^2 \theta + \kappa^2 \cos^2 \theta - E^2 \sin^2 \theta} \), \( f_2 = E(1 - \kappa^2) \cos \theta \sin^2 \theta \) and \( f_3 = \frac{\sqrt{2\sigma_{MS}}}{a} \left( \sin^2 \theta + \kappa^2 \cos^2 \theta \right) \) are some functions of \( \theta \), \( \text{erf}(x) \) is the well known error function defined as \( \text{erf}(x) = \int_0^x \exp(-t^2) dt \), \( E_D = \frac{d_D}{R_D} \) and \( \Omega \) is the normalizing constant such that \( \int_0^{2\pi} p_\theta(\theta) d\theta = 1 \).

In (3.31), the semi-major axis for the local Eccentro-Scattering disc \( a \) and the radius of the distant scattering disc \( R_D \) do not change with distances \( d \) and \( d_D \) and remain constant as far as the terrain and clutter do not change in the scattering regions, so the pdf of AoA of the multipaths at BS in macrocells depends on:

1. The eccentricity of the local Eccentro-Scattering disc (and the eccentricity of the distant Eccentro-Scattering disc if circular disc is not assumed, i.e. \( e_D \neq 0 \)),
3.3 Angle Of Arrival For Macrocell Environment

Figure 3.7: *Simulated and theoretical pdf of AoA for suburban macrocell with d = 2000m, a = 300m, D = 5000m, a_D = 150m, and \( \theta_D = 15^\circ \).*

2. The ratios \( E \) and \( E_D \),

3. The standard deviations of the scattering points around MS and of those around the center of the distant disc.

In (3.27) and (3.31), \( \theta_D \) plays an important role in describing the total angle spread when both local and distant scatterers are taken into account. \( \theta_D \) usually remains constant and indicates the deviation of the center of the dominant distant scattering cluster from the center of the mobile service area. If \( \theta_D \) is large as compared to the values of \( \theta_{L,\text{max}} \) and \( \theta_{D,\text{max}} \), then the use of two separate directional antennas is a valid recommendation when a fixed beam antenna system is used at BS, see Fig. 3.6. However a smart antenna can handle multiple beams, therefore the use of two directional antennas may not be needed. Thus,
3.3 Angle Of Arrival For Macrocell Environment

(3.27) and (3.31) are helpful in designing antenna systems in flat rural, suburban, urban, and hilly areas. If $\theta_D - \theta_{D,\text{max}}$ is less than $\theta_{L,\text{max}}$ then the pdf of AoA would be the addition of $p_{\text{G}}^{(L)}(\theta)$ and $p_{\text{G}}^{(D)}(\theta)$ for the overlapping region. In Fig. 3.7, simulation and theoretical results, using (3.27) and (3.31), are presented for typical macrocell environments both for uniform and Gaussian distributions. Keeping the assumptions itemized in section 2.2 of the previous chapter in view, we use re-radiating scattering structures in our simulations. We exploit mainly reflection and diffraction phenomena over 2 GHz frequency, i.e. 15 cm wavelength. At this wavelength all scattering structures mostly buildings, trees and buses look like big opaque or quasi-opaque spheres which reflect and diffract radio waves at 2 GHz. Normalized histograms of the number of scattering occurrences are sketched in the plots using point markers against their respective angles.

The following additional remarks can be made about (3.27) and (3.31):

1. The work in [27] derived the pdf of AoA of the multipath signals at BS considering scattering points that are Gaussian distributed around MS only, and within the angular beamwidth of a directional antenna at BS. But no geometrical shape of the scattering disc was defined, which is an impractical assumption as discussed earlier. The only effect of using a directional antenna at BS is to reject the AoAs falling outside the beamwidth, while it does not alter the distribution of AoA at BS. However, by substituting $\theta_{L,\text{max}}$ by $\alpha$, the half beamwidth of the directional antenna, used at BS in (3.28) we get results obtained in [27].
3.3 Angle Of Arrival For Macrocell Environment

2. If we consider $\sigma_{MS} \geq 3a$ and $\sigma_D = 0$, (3.31) approaches the results found by Piechocki, Tsoulos and McGeehan [28] for bounded uniformly distributed scatterers confined in an elliptical scattering disc. Also if we exclude distant scattering clusters, (3.27) gives the same results found in [28].

3. The work in [3] for the uniformly distributed local scatterers confined in circular disc in macrocells can be derived either by putting $a = b = R$ in (3.27) or by substituting $\sigma_{MS} \geq 3a$, $\sigma_D = 0$, and $a = b = R$ in (3.31).

4. In macrocell environments where BS antennas are not at higher altitudes, e.g. in urban areas as compared to rural areas, the scatterers in the vicinity of BS have significant impact on the pdf of AoA. Then using JGSM approach, the pdf of AoA of the multipath signals at BS is,

$$p_\Theta(\theta) = \frac{1}{3} \left( P_\Theta^{(BS)}(\theta) + P_\Theta^{(MS)}(\theta) + P_\Theta^{(D)}(\theta) \right)$$

(3.32)

where the sum $P_\Theta^{(MS)}(\theta) + P_\Theta^{(D)}(\theta)$ is given in (3.31) while,

$$P_\Theta^{(BS)}(\theta) = \frac{1}{2\pi} \left\{ 1 - \exp \left( \frac{a_{BS}^2 b_{BS}^2}{2(a_{BS}^2 \sin^2 \theta + b_{BS}^2 \cos^2 \theta)\sigma_{BS}} \right) \right\}$$

(3.33)

In (3.33), $a_{BS}$ and $b_{BS}$ are the semi-major and semi-minor axes of the Eccentro-Scattering disc around BS.

These results illustrate furthermore, the generality of the Eccentro-Scattering model.

As mentioned earlier, the maximum delay of the multipaths ($\tau_{max}$) has a significant effect on the pdf of AoA at BS. The pdf of AoA derived using the Eccentro-Scattering model...
depends on the size of the Eccentro-Scattering disc, which in turn depends on $\tau_{\text{max}}$, whereas this is not the case for the corresponding pdf derived using unbounded scattering [2, 16, 27]. It was mentioned in [2] that, in the Gaussian AoA model, the distribution of arriving waves in azimuth is assumed to be Gaussian without specific mention of the scatter density required to produce it. Nevertheless it was stated earlier in [54] that, if the Gaussian model for the distribution of scatterers round the mobile is assumed then the angular distribution seen from BS is also Gaussian. In fact, if we consider unbounded scatterers or multipaths from infinitely far distant scatterers, we get an exactly bell-shaped Gaussian pdf of AoA of the multipaths at BS. However if we consider Gaussian distributed scatterers confined in some disc i.e. the Eccentro-Scattering disc, then the pdf of AoA would be Gaussian distributed with its feet depending on the size of the disc, the distance between BS and MS, and the standard deviation of the scattering points around MS and BS under the zooming effect, see Fig. 3.3 and Table 3.1.

An interesting general result in picocell, microcell, and macrocell environments, is the similarity of the plots of the pdf of AoA for uniform and Gaussian scattering when the standard deviation of the Gaussian distributed scatterers around MS is greater than twice the semi-major axis of the respective Eccentro-Scattering discs. In other words, assuming scattering to be either uniformly or Gaussian distributed for sparsely populated areas gives almost the same distribution of AoA of multipaths at BS, see Fig. 3.4.
### Table 3.1: Summary of the Spatial Channel Models

<table>
<thead>
<tr>
<th>Environment</th>
<th>Respective Models</th>
<th>Used Scatter Distribution</th>
<th>Corresponding Eccentro-Scattering Model substitution</th>
<th>Most common shape of the plot of AoA distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macrocell Rural</td>
<td>Petrus [26], Ertel [3], and Piechocki [28]</td>
<td>Uniform</td>
<td>$a = b = R$ in (3.27) OR $\sigma_{MS} = 3a, \sigma_{BS} = \sigma_{D} = 0$, and $a = b = R$ in (3.31)</td>
<td><img src="image1" alt="Distribution" /></td>
</tr>
<tr>
<td>Urban/Suburban</td>
<td>Petrus [26], Ertel [3], and Piechocki [28]</td>
<td>Uniform</td>
<td>$a = b = R$ in (3.27) OR $\sigma_{MS} = 3a, \sigma_{BS} = \sigma_{D} = 0$, and $a = b = R$ in (3.31)</td>
<td><img src="image2" alt="Distribution" /></td>
</tr>
<tr>
<td></td>
<td>Janaswamy [2] and Lotter [27]</td>
<td>Gaussian</td>
<td>$a = 4\sigma_{MS}, \sigma_{BS} = \sigma_{D} = 0$ in (3.31)</td>
<td><img src="image3" alt="Distribution" /></td>
</tr>
<tr>
<td>Hilly Petrus [26], Ertel [3], and Piechocki [28]</td>
<td>Uniform</td>
<td>$a = b = R$ in (3.27) OR $\sigma_{MS} = 3a, \sigma_{BS} = \sigma_{D} = 0$, and $a = b = R$ in (3.31)</td>
<td><img src="image4" alt="Distribution" /></td>
<td></td>
</tr>
<tr>
<td>Microcell</td>
<td>Liberti [24] and Ertel [3]</td>
<td>Uniform</td>
<td>$e = \frac{d}{za}$ in (3.10) OR $\sigma_{MS} = 3a, \sigma_{BS} = \sigma_{D} = 0$ in (3.17)</td>
<td><img src="image5" alt="Distribution" /></td>
</tr>
<tr>
<td></td>
<td>Janaswamy [2] and Lotter [27]</td>
<td>Gaussian</td>
<td>$a = 4\sigma_{MS}, \sigma_{BS} = \sigma_{D} = 0$ in (3.17)</td>
<td><img src="image6" alt="Distribution" /></td>
</tr>
<tr>
<td>Picocell</td>
<td>Liberti [24] and Ertel [3]</td>
<td>Uniform</td>
<td>$e = \frac{d}{za}$ in (3.10) OR $\sigma_{MS} = 3a, \sigma_{BS} = \sigma_{D} = 0$ in (3.17)</td>
<td><img src="image7" alt="Distribution" /></td>
</tr>
<tr>
<td></td>
<td>Janaswamy [2] and Lotter [27]</td>
<td>Gaussian</td>
<td>$a = 4\sigma_{MS}, \sigma_{BS} = \sigma_{D} = 0$ in (3.17)</td>
<td><img src="image8" alt="Distribution" /></td>
</tr>
<tr>
<td>Effect of Directional Antenna at BS</td>
<td>Lotter [27]</td>
<td>Gaussian</td>
<td>$z_1 = 0, z_2 = \infty$, and, $\theta_{L,\text{max}} = \alpha$ in (3.28), where $\alpha = \text{half of the beamwidth of directional antenna}$</td>
<td><img src="image9" alt="Distribution" /></td>
</tr>
</tbody>
</table>
3.4 Modeling the Impact of Scattering around BS on the AoA Statistics

Table 3.1 summarizes the results and comparisons of the Eccentro-Scattering model with previous physical channel models. Also in Table 3.1, the most common shapes of the pdf of AoA of the multipaths at BS are given for all cellular environments in Gaussian distributed scattering, which depend on $\sigma_{MS}$, $\sigma_{BS}$, $e$, and $E$ of the Eccentro-Scattering discs. The work in [2, 3, 16, 24, 27, 28] can easily be extracted from Table 3.1.

3.4 Modeling the Impact of Scattering around BS on the AoA Statistics

In this section, we address the issue of the impact of heavy scattering around BS on the AoA statistics of multipath signals at BS. We utilize JGSM proposed in chapter 2, along with a scattering-free region, which makes it feasible to model the effect of scattering around BS on the azimuthal distribution. This combination successfully answers the formation of pdf tails on both sides of the mean angle of arrival in the measurements performed by Pedersen et al. [4] for an urban macrocell environment. JGSM along with the provision of scattering-free region, provides simpler modeling as compared to the Gaussian Macrocell Eccentro-Scattering model in section 3.3.2, where Gaussian distributed scatterers are confined in an elliptical or circular disc. In Gaussian Macrocell Eccentro-Scattering model, the eccentricity of the Eccentro-Scattering disc is adjusted to provide appropriate modeling for a specific cellular environment, which makes it more complicated than the combination of JGSM and
3.4 Modeling the Impact of Scattering around BS on the AoA Statistics

3.4.1 Low Antenna-Height Urban Macrocell Model

Fig. 3.8 depicts the proposed scattering model where BS and MS are surrounded by Gaussian distributed scatterers represented by two separate Gaussian functions.

Let $R_{null}$ be the radius of circular shaped scattering-free zone around BS as shown in Fig. 3.8. The value of $R_{null}$ depends on the radius of the cell, height of BS antenna, clustering of the structures around BS, and the terrain of BS location.

A Gaussian model of the spatial pdf of the scatterers around MS and BS is written in (2.4) and (2.9), respectively.
3.4 Modeling the Impact of Scattering around BS on the AoA Statistics

The area bounded by the sector $BSQ$ in Fig. 3.8 is a function of the angle $\theta$, with angles between $\beta$ and $\theta_{\text{max}}$, where $\theta_{\text{max}}$ is the maximum angle of arrival and gives the measure for the maximum angular spread. For indoor picocells, multipath signals arrive at BS from all directions, i.e. $\theta \in \{-180^\circ, 180^\circ\}$. For outdoor microcells, a directional antenna of half beamwidth $\alpha = 60^\circ$ is usually used keeping the maximum angular spread as $120^\circ$. Whereas in outdoor macrocells, the maximum AoA, $\theta_{\text{max}}$, and the minimum AoA, $\theta_{\text{min}}$, depend on the standard deviation of the distribution of the scatterers around MS, the distance between BS and MS and the angle $\beta$, as,

$$\theta_{\text{max,min}} \approx \beta \pm \arcsin\left(\frac{4\sigma_{MS}}{d}\right), \text{for } \sigma_{MS} \leq \frac{d}{4}$$

(3.34)

Considering (2.4) and the geometry in Fig. 3.8, the density of the scattering points around MS can be described by the bivariate Gaussian distribution,

$$p_{R_{BS},\theta}^{(\text{MS})}(r_{BS}, \theta) = \begin{cases} \frac{r_{BS}}{2\pi\sigma_{MS}^2} \exp\left(-\frac{r_{BS}^2 + d^2 - 2r_{BS}d\cos(\theta - \beta)}{2\sigma_{MS}^2}\right), & \text{for } r_{BS} > 0 \\ 0, & \text{elsewhere} \end{cases}$$

(3.35)

In a similar way, considering (2.9) and the geometry in Fig. 3.8, the density of the scattering points around BS can be found as,

$$p_{R_{BS},\theta}^{(\text{BS})}(r_{BS}, \theta) = \begin{cases} \frac{r_{BS}}{2\pi\sigma_{BS}^2} \exp\left(-\frac{r_{BS}^2}{2\sigma_{BS}^2}\right), & \text{for } r_{BS} > 0 \\ 0, & \text{elsewhere} \end{cases}$$

(3.36)

From (3.35), (3.36) and Fig. 3.8, the Cumulative Distribution Function (CDF) of the scattering points around MS and BS would be, respectively,
3.4 Modeling the Impact of Scattering around BS on the AoA Statistics

\[
P^{(MS)}_\Theta(\theta) = \int_{\theta_{min}}^{\theta} \int_{0}^{\infty} \frac{r_{BS}}{2\pi\sigma^2_{MS}} \exp\left(-\frac{r^2_{BS} - d^2 + 2r_{BS}d\cos(\zeta - \beta)}{2\sigma^2_{MS}}\right) dr_{BS} d\zeta \tag{3.37}
\]

and

\[
P^{(BS)}_\Theta(\theta) = \int_{\theta_{min}}^{\theta} \int_{R_{null}}^{\infty} \frac{r_{BS}}{2\pi\sigma^2_{BS}} \exp\left(-\frac{r^2_{BS}}{2\sigma^2_{BS}}\right) dr_{BS} d\zeta \tag{3.38}
\]

We assume that the received signal at BS antenna interacts with one single scatterer in the last reflection/scattering, therefore the AoA of the multipaths from scatterers around BS and MS are two disjoint events. Hence, the pdf of AoA of the multipaths from all scattering points, \( p_\Theta(\theta) \), will be basically the addition of the derivatives of (3.37) and (3.38) with respect to \( \theta \), i.e.,

\[
p_\Theta(\theta) = \frac{1}{2} \left( p^{(MS)}_\Theta(\theta) + p^{(BS)}_\Theta(\theta) \right) = \frac{1}{2} \left( \frac{d}{d\theta} p^{(MS)}_\Theta(\theta) + \frac{d}{d\theta} p^{(BS)}_\Theta(\theta) \right) \tag{3.39}
\]

therefore,

\[
p_\Theta(\theta) = \frac{1}{2} \int_{0}^{\infty} \frac{r_{BS}}{2\pi\sigma^2_{MS}} \exp\left(-\frac{r^2_{BS} - d^2 + 2r_{BS}d\cos(\theta - \beta)}{2\sigma^2_{MS}}\right) dr_{BS}

+ \frac{1}{2} \int_{R_{null}}^{\infty} \frac{r_{BS}}{2\pi\sigma^2_{BS}} \exp\left(-\frac{r^2_{BS}}{2\sigma^2_{BS}}\right) dr_{BS} \tag{3.40}
\]

Simplifying (3.40), we get the pdf of AoA of the multipaths at BS from the Gaussian distributed scatterers around BS and MS as,

\[
p_\Theta(\theta) = \frac{\Omega}{4\pi} \left\{ \sqrt{\frac{\pi}{2\sigma_{MS}}} \frac{d}{\sigma_{MS}} \cos(\theta - \beta) \exp\left(-\frac{d^2}{2\sigma^2_{MS}}\cos^2(\theta - \beta)\right) \text{erfc}\left(-\frac{d\cos(\theta - \beta)}{\sqrt{2\sigma^2_{MS}}}\right)

+ \exp\left(-\frac{d^2}{2\sigma^2_{MS}}\right) + \exp\left(-\frac{R^2_{null}}{2\sigma^2_{BS}}\right) \right\} \tag{3.41}
\]

82
where $\Omega$ is normalizing constant such that $\int_0^{2\pi} p_{\theta}(\theta) d\theta = 1$, and erfc($x$) is the complementary error function defined as: $\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp(-t^2) dt$.

### 3.4.2 Results and Discussion

In outdoor environments, the majority of scattering points are clustered together with their density decreases as the distance from MS increases. This fact suggests a Gaussian model for the distribution of scatterers in outdoor environments. Since the distribution of AoA in outdoor environments strictly depends on the separation between BS and MS and the nature of scattering structures; so, we use different values for $R_{\text{null}}$ in our proposed scattering model to represent rural, suburban/bad urban, and urban environments as listed in Table 3.2. Equation (3.41) represents the general closed-form expression for the pdf of AoA of the multipaths at BS using the proposed scattering model. The following remarks can be made regarding this formula:

1. We observe that the second and third terms in equation (3.41), which do not depend on the AoA, $\theta$, reveal the fact that the tails of the pdf of the AoA are usually uniform, and their height can be easily controlled by the appropriate selection of $R_{\text{null}}$.

2. If we consider $\sigma_{MS} = \infty$ and $\sigma_{BS} = 0$, pdf in (3.41) approaches a uniform distribution for the AoA of the multipaths at BS. This is a common assumption made usually to study the Doppler characteristics of the channel and is based on the fact that
### 3.4 Modeling the Impact of Scattering around BS on the AoA Statistics

**Figure 3.9:** *pdf of AoA at BS in urban macrocell mobile environments*
3.4 Modeling the Impact of Scattering around BS on the AoA Statistics

multipaths are arriving from all directions with equal probabilities.

3. If we consider either $\sigma_{BS} = 0$ or $R_{null} > 4\sigma_{BS}$, pdf in (3.41) approaches the result found by Janaswamy [2] for Gaussian distributed scatterers located around MS only.

4. The work in [27] derived the pdf of AoA of the multipaths at BS considering scattering points that are Gaussian distributed and situated around MS within the angular beamwidth, $2\alpha$, of a directional antenna at BS. The only effect of using directional antenna at BS is the rejection of the AoAs falling outside the beamwidth of the antenna, with no alteration of the distribution of AoA at BS. However, by substituting $\theta_{max}$ by $\alpha$ in (3.41), we get the same results obtained in [27].

5. In [2, 4], a Gaussian function with standard deviation of $6^\circ$ was suggested to fit field measurements performed in Aarhus, Denmark, which provided a good match except for the tails of the histogram. It was observed that the tails were actually heavier than predicted by Gaussian distribution. In fact, these tails are formed due to the multipath signals reflected by the scatterers situated around BS. The height of these tails depends on the standard deviation of the Gaussian distributed scatterers around BS, $\sigma_{BS}$, and the value of $R_{null}$. A lower value of $R_{null}$ produces heavier tails and vice versa. Equation (3.41) explains the formation of the tails, which is due to the AoA bouncing from the scatterers in the vicinity of BS.

In Fig. 3.9(a) and 3.9(b), plots for the rate of occurrence of AoA of the multipaths at BS have been presented using Uniform Scattering Model [3, 28], the Gaussian Scatter Density
3.5 Conclusion

<table>
<thead>
<tr>
<th>Environment</th>
<th>Proposed Range of $R_{\text{null}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outdoor Macrocellular Rural Area</td>
<td>$R_{\text{null}} &gt; 4\sigma_{BS}$</td>
</tr>
<tr>
<td>Sub Urban/Bad Urban</td>
<td>$3\sigma_{BS} &lt; R_{\text{null}} \leq 4\sigma_{BS}$</td>
</tr>
<tr>
<td>Urban</td>
<td>$1\sigma_{BS} &lt; R_{\text{null}} \leq 3\sigma_{BS}$</td>
</tr>
</tbody>
</table>

Model (GSDM) [2] and the proposed scattering model besides measurement data [4]. The first conclusion we can make from these plots is that Gaussian assumption for the distribution of scatterers in outdoor environment is more appropriate as compared to uniform assumption. Fig. 3.9(b), enlightens the tails of the distribution of AoA, on logarithmic scale. Here, we can observe the effect of scattering around BS, which is successfully overcome by adjusting the value of $R_{\text{null}}$ in the proposed scattering Model.

3.5 Conclusion

In this chapter, we have studied the spatial characteristics of cellular mobile channel for picocell, microcell, and macrocell environments assuming uniform and Gaussian distribution for the scatterers. We have utilized the Eccentro-Scattering Model proposed in the previous chapter and derived general expressions for the pdf of AoA of the multipath signals at BS applicable to picocell, microcell, and macrocell environments assuming uniform and Gaussian scatter density. The same methodology can be further used to derive the spatial statistics.
of the mobile channel for a 3-D environment. The derived results show that the previous spatial models can easily be extracted from our proposed model with appropriate selection of parameters. We have thoroughly discussed the results and compared them with those of all existing models.

Theoretical results when compared with some available measurements both in indoor and outdoor environments, show good proximity with the realistic situations. We can thus visualize our proposed model to be useful in simulating several propagation scenarios for wireless communications systems. The derived results, in closed form, can also be used in further research work to model Doppler characteristics and tracking properties of time-varying fading channels.

We have also addressed the issue of the impact of local-to-BS scattering on the spatial characteristics and implemented JGSM for low antenna-height urban environment by introducing an adjustable scattering-free region around BS. The adjustable scattering-free region around BS models the extent of scattering in the vicinity of BS and thus can easily be used as a control-valve for the inclusion/exclusion of scattering objects in the vicinity of BS according to their anticipated effect on the angular distribution of the cellular mobile channel. We have found that the JGSM along with the provision of scattering-free region provides good fitness to the field measurements when compared with all existing Gaussian scattering models that consider only one Gaussian function for the distribution of scatterers around MS.
Chapter 4

Characterization of Angle Spread

Section 4.1 of this chapter presents an overview of the significance of angle spread in MIMO channel modeling and itemizes the contributions made in the chapter. Section 4.2 discusses various definitions of angle spread, which are already being used in the literature. In section 4.3, a novel method for quantifying angle spread of multipath power is proposed and its relations with the previous definitions are discussed. Section 4.4 presents the effect of AoA distribution truncation on the angle spread, while section 4.5 itemizes various factors that cause the truncation of AoA distributions. Section 4.6 compares different azimuthal models with the measurement campaigns on the basis of angle spread and section 4.7 concludes the chapter and presents final remarks.
4.1 Overview

Use of adaptive antenna arrays in MIMO communication systems has generated significant interest in recent years. MIMO systems utilizing advanced diversity and spatial filtering schemes [55], offer very high information-theoretic capacities [18, 37]. The optimum antenna array topology and combining algorithm are strongly related to the azimuth dispersion of the mobile radio channel [4], especially during small-scale fading. Hence, in order to make realistic evaluations of the capabilities of diversity and spatial filtering schemes in MIMO systems, deep understanding of the statistics of the azimuth angle spread is required.

Angle spread is the key factor of the second order statistics (or the correlation statistics) of fading processes in wireless communications [22, 23, 33, 49]. The concept of isotropic scattering or omni-directional azimuthal propagation modeling [23] does not cope with the realistic situations anymore, therefore a lot of work has been done on non-isotropic spatial channel models [30, 38, 49, 56] to simulate the angular energy distribution at BS antenna (or antenna array). Use of these angular energy distributions in the mathematical calculations for spatial fading correlations, opened a new debate on finding the exact definition of angle spread in the research community. Various definitions of the angle spread have been used in the literature so far, but unfortunately none of them is capable of establishing a generalized relationships among different parameters of the angle spread and multipath fading. This motivated us to focus on the spatial statistics of the cellular mobile channel and introduce a generalized definition of the angle spread for its diverse use in correlation calculations.
Main contributions of this chapter are thus summarized as follows:

1. We discuss all previous definitions of the angle spread and propose a novel generalized method of quantifying the angle spread of the multipath power. Our method provides almost all parameters of the dispersion of multipath power in space, which can be further used for calculating more accurate spatial correlations and other statistics of multipath fading channels. These proposed parameters are also helpful in finding the exact standard deviation of truncated or distorted angular distributions as well as of the angular data acquired in measurement campaigns, which can lead to the computation of the exact separation distances among array elements needed for diversity antennas.

2. Keeping the recent use of truncated Gaussian and Laplacian functions as the distributions of AoA in view, we indicate the severity of the effects of distribution truncation on the angle spread.

3. We itemize the factors which cause such truncations in the AoA distributions and provide analytical solution to compensate for their effects.

4. We propose the angle spread as the goodness-of-fit measure in measurement campaigns and show the comparisons of some notable azimuthal models with the measurement results.
4.2 Angle Spread

Multiple replicas of the transmitted signal are received at the receiver due to the multipath propagation in the radio environment. These multipath components of the received signal arrive at the receiver antenna from different azimuth directions about the horizon [22, 23, 49]. The distribution of these multipath components in the azimuth is conveniently described by the function, $p(\theta)$, where $\theta$ is the azimuthal angle of arrival (AoA) [32].

Depending on their choices and requirements, the researchers are currently using several definitions of quantifying angle spread in multipath fading channels. These definitions involve total angular span [29], beamwidth, the rms value of the angular data, standard deviation of Gaussian [30] or Laplacian distribution [31] and shape factor defined in [32, 33]. However, no clear and unanimous definition has yet appeared in the literature.

Use of Beamwidth and rms value as the definition of angle spread are often ill suited for general application to periodic functions such as angle of arrival (AoA) distributions [33]. Standard deviation (SD), $\sigma_\theta$, of the Gaussian angular energy distribution heavily depends on the total angular span, $\theta_{\text{span}}$, and the degree of truncation of the distribution (if there is any truncation in the distribution). So the utilization of SD of an exact bell-shaped Gaussian function as the true SD of the angular data which represents a truncated Gaussian, will certainly lead to wrongful results.

The shape factor $\Lambda$ defined in [32, 33] (we are keeping the same notation) used to denote
4.3 The Proposed Method to Quantify Angle Spread

the angle spread in the range from zero to one, can be considered as the most favorable one, since it is invariant under the changes in transmitted power, under any series of rotational or reflective transformation of \( p(\theta) \) [33]. However, this definition has the disadvantage of not providing true physical information about the angle spread, i.e. information either in degrees or radians. This disadvantage is the main cause of its unpopularity in the research community. We will show in sequel that one of our parameter in the proposed angle spread modeling resembles this definition and gives the same results.

4.3 The Proposed Method to Quantify Angle Spread

Our method of quantifying angle spread is based on Fourier coefficients of \( p(\theta) \), and is analogous to the method used in [32]. However, we utilize trigonometric moments for calculating the statistics of directional data in [57] instead of exponential moments. It can easily be shown that both methods generate the same Fourier coefficients. Since the use of trigonometric moments is advantageous in manipulating discrete data, we will later extend our method from continuous distribution to the discrete data obtained in measurements.

Let \( \bar{R}_n = \bar{C}_n + j\bar{S}_n \) be defined as the \( n \)th complex trigonometric moment of the angular energy distribution \( p(\theta) \) whose total power is equal to \( P_0 = \int_0^{2\pi} p(\theta)\,d\theta \). The trigonometric parameters, \( \bar{C}_n \) and \( \bar{S}_n \) for the angular energy distribution \( p(\theta) \) are defined as
4.3 The Proposed Method to Quantify Angle Spread

\[
\bar{C}_n = \frac{1}{P_0} \int_0^{2\pi} p(\theta) \cos(n\theta) d\theta \quad (4.1)
\]

and

\[
\bar{S}_n = \frac{1}{P_0} \int_0^{2\pi} p(\theta) \sin(n\theta) d\theta \quad (4.2)
\]

In case of discrete measured or observed data, the definitions for the trigonometric parameters, \( \bar{C}_n \) and \( \bar{S}_n \) can be modified as

\[
\bar{C}_n = \frac{1}{F_0} \sum_{i=1}^{N} f_i \cos(n\theta_i) \quad (4.3)
\]

and

\[
\bar{S}_n = \frac{1}{F_0} \sum_{i=1}^{N} f_i \sin(n\theta_i) \quad (4.4)
\]

where \( F_0 = \sum_{i=1}^{N} f_i \) for \( i = 1, \cdots, N \) and \( f_i \) is the number of occurrences for the AoA \( \theta_i \) in the \( i \)th bin of histogram.

\( \bar{R}_n \) can also be written as,

\[
\bar{R}_n = |\bar{R}_n| e^{j\bar{\theta}_n} \quad (4.5)
\]

where \( |\bar{R}_n| = \sqrt{\bar{C}_n^2 + \bar{S}_n^2} \) is the mean resultant of the \( n \)th trigonometric moment and \( \bar{\theta}_n = \tan^{-1} \left( \frac{\bar{S}_n}{\bar{C}_n} \right) \) is its direction [57]. If the first moment is considered, \( \bar{\theta}_1 \) gives the mean angle of the distribution, \( p(\theta) \), i.e. the mean AoA in our case. From now onward, we will denote \( \bar{\theta}_1 \) as \( \bar{\theta} \), the mean AoA. Furthermore, we will utilize only first and second moments in our characterization of angle spread.
4.3 The Proposed Method to Quantify Angle Spread

Now we define our basic measure of angular dispersion, the circular variance, \( S_0 \) as,

\[
S_0 = 1 - |\bar{R}_1| \quad (4.6)
\]

where \( |\bar{R}_1| \) is the magnitude of the first trigonometric moment of \( p(\theta) \). \( S_0 \) is invariant under the changes in transmitted power, under any series of rotational or reflective transformation of \( p(\theta) \). We see that \( 0 \leq S_0 \leq 1 \), which means that the observed AoAs are tightly clustered about the mean direction \( \tilde{\theta} \), then \( |\bar{R}_1| \) will be closer to 1 and \( S_0 \) will be nearly zero. On the other hand, if the AoAs are widely dispersed then \( |\bar{R}_1| \) will be small and \( S_0 \) will be nearly 1.

\( S_0 \) and \( |\bar{R}_1| \) can easily be transformed to the shape factor \( \Lambda \) discussed in [32] and the conventional definition of standard deviation, as

\[
\Lambda = \sqrt{1 - |\bar{R}_1|^2} = \sqrt{2S_0 - S_0^2} \quad (4.7)
\]

and

\[
\sigma_\theta = \sqrt{-2 \ln(1 - S_0)} = \sqrt{-2 \ln(|\bar{R}_1|)} \quad (4.8)
\]

where \( \sigma_\theta \) is the conventional standard deviation of the angular energy distribution in radians. It gives the true physical information about the angular dispersion of the data. It is also invariant under the circumstances discussed for \( S_0 \). Since it provides true physical information about the dispersion of the multipath signals in space, it can also stand as the major candidate for the unanimous definition of angle spread of multipath signals. If \( \sigma_\theta \) is
4.4 Effect of Distribution Truncation on the Angle Spread

already known, then the circular variance $S_0$ and the mean resultant of the first moment $|\bar{R}_1|$ can also be deduced as,

$$S_0 = 1 - e^{-\frac{\sigma^2_\theta}{2}}$$  \hspace{1cm} (4.9)

$$|\bar{R}_1| = e^{-\frac{\sigma^2_\theta}{2}}$$  \hspace{1cm} (4.10)

The shape factor $\Lambda$ and $\sigma_\theta$ are also inter-related as,

$$\sigma_\theta = \sqrt{-\ln(1 - \Lambda^2)}$$  \hspace{1cm} (4.11)

$$\Lambda = \sqrt{1 - e^{-\sigma^2_\theta}}$$  \hspace{1cm} (4.12)

In [33], Durgin et al. have also proposed two more shape factors angular constriction $\gamma$ and orientation parameter $\theta_{MF}$ in their study. $\gamma$ is a measure of how multipath concentrates about two azimuthal directions and $\theta_{MF}$ provides the azimuthal direction of maximum fading. These two parameters can also be related to the complex trigonometric moments as,

$$\gamma = \frac{|\bar{R}_2 - \bar{R}_1^2|}{1 - |\bar{R}_1|^2}$$  \hspace{1cm} (4.13)

and

$$\theta_{MF} = \frac{1}{2} \text{phase}\{\bar{R}_2 - \bar{R}_1^2\}$$  \hspace{1cm} (4.14)

4.4 Effect of Distribution Truncation on the Angle Spread

It has been observed in [54] that if the bell-shaped spatial Gaussian model for the distribution of scatterers around the mobile is assumed, then the angular distribution as seen from the BS
4.4 Effect of Distribution Truncation on the Angle Spread

Figure 4.1: *Comparison between truncated ($\theta_{\text{span}} = 90^\circ$) and untruncated ($\theta_{\text{span}} = 360^\circ$) Gaussian density functions, $\sigma_g = 30^\circ$, $\bar{\theta} = 45^\circ$*

is also Gaussian. Based on the measurements, Pedersen *et al.* [4] found that the scattering structures in urban environments usually give rise to the Gaussian distribution in azimuthal angle of arrival and the Laplacian distribution in power azimuthal spectrum (PAS). Laplacian function was also considered the best candidate for the distribution in angle of arrival in indoor environments [1]. However, many situations have been observed when neither the distribution of the angle of arrival matches exactly a true bell-shaped Gaussian nor the PAS fits an exact double exponential Laplacian function, then a truncated Gaussian or Laplacian function is usually considered as an approximate solution. Such situations usually emerge in outdoor environment when Gaussian distributed scatterers do not produce exact Gaussian distributions in AoA at BS, but instead they form some truncated, distorted, cut
or constant-added versions of Gaussian distributions. Measurements in [4, 56] show that in addition to bell-shaped Gaussian distribution in AoA, there is always some additional part, which distorts the Gaussian function. This additional part certainly disturbs the angle spread measure. That is why the SD of the exact bell-shaped Gaussian function, $\sigma_g$, can not be trusted any more to be used in calculating the spatial fading correlations among antenna array elements. If it is still used, the spatial fading correlation calculations will certainly result in wrong separations for diversity antennas.

The true SD, $\sigma_\theta$, of the angular energy distribution or the pdf of the AoA as seen at BS, depends on the peak/s of the distribution, as well as on the angular span of the angular data. SD of the exact bell-shaped Gaussian function, $\sigma_g$, remains equal to the true SD, $\sigma_\theta$, of the Gaussian azimuthal distribution as long as the total angular span, $\theta_{\text{span}}$, remains more than $8\sigma_g$ (or twice of $4\sigma_g$). Angular span, $\theta_{\text{span}}$, can be written as,

$$\theta_{\text{span}} = \theta_{\text{max}} - \theta_{\text{min}} \quad (4.15)$$

where $\theta_{\text{max}}$ and $\theta_{\text{min}}$ are the maximum and minimum angles of arrival, respectively.

As soon as the angular span lowers $8\sigma_g$ (in case of a truncated Gaussian), the true SD of the angular energy starts decreasing, and it decreases very sharply for the smaller values of the span.

A truncated Gaussian function is defined in terms of angular span as,

$$p_\theta^{(G)}(\theta) = \frac{C_g}{\sqrt{2\pi}\sigma_g} \exp\left(-\frac{(\theta - \bar{\theta})^2}{2\sigma_g^2}\right) \quad (4.16)$$
4.4 Effect of Distribution Truncation on the Angle Spread

Figure 4.2: Effect of Gaussian distribution truncation on the angle spread

where $\bar{\theta}$ is the mean AoA and $C_g$ is the normalizing constant chosen to make $\tilde{p}_\Theta^{(G)}(\theta)$ a density function. In Fig. 4.1, a truncated Gaussian density function is plotted along with a full-span or untruncated Gaussian density function. $C_g$ is given as,

$$C_g = \frac{1}{\text{erf}\left(\frac{\theta_{\text{span}}}{2\sqrt{2}\sigma_g}\right)} \quad (4.17)$$

In equation (4.16), $\sigma_g$ defines the probability density function (pdf), $\tilde{p}_\Theta^{(G)}(\theta)$, but does not provide the correct information about the deviation of the data from the mean AoA, $\bar{\theta}$. $\sigma_g$ is in fact the SD of the untruncated or full-span Gaussian with $\theta_{\text{span}} = 8\sigma_g$. For such untruncated case, $C_g$ will be equal to 1, otherwise it will always be greater than 1.

After some mathematical manipulations given in Appendix 4-A, the true SD, $\sigma_\theta$, for the
4.4 Effect of Distribution Truncation on the Angle Spread

Figure 4.3: Comparison between truncated (θ_{span} = 90°) and untruncated (θ_{span} = 360°) Laplacian density functions, σ_l = 30°, ă = 45°

Truncated Gaussian function, \( \tilde{p}_G(\theta) \), can easily be related to the SD of full-span Gaussian function, \( \sigma_g \), as,

\[
\sigma_\theta^2 = \sigma_g^2 - \frac{C_g \theta_{span} \sigma_g}{\sqrt{2\pi}} \exp \left( -\frac{\theta_{span}^2}{8\sigma_g^2} \right)
\]  \hspace{1cm} (4.18)

Fig. 4.2 shows the effect of truncation of the Gaussian function on the angle spread measured as the true SD, \( \sigma_\theta \), using various values of \( \sigma_g \). Fig. 4.2 also provides the corresponding effect for the case of uniform distribution in AoA. We observe that the effect of decreasing angular span, \( \theta_{span} \), on the angle spread \( \sigma_\theta \) in case of uniform distribution is linear as expected from the definition, \( \sigma_\theta = \theta_{span}/(2\sqrt{3}) \). On the other hand, the decreasing \( \theta_{span} \) clearly affects \( \sigma_\theta \) for large values of \( \sigma_g \) in case of Gaussian distribution, but does not affect
4.4 Effect of Distribution Truncation on the Angle Spread

$\sigma_\theta$ for small values of $\sigma_g$. One more interesting result that can be observed is the curve of $\sigma_\theta$ versus $\theta_{\text{span}}$ for Gaussian distribution follows the linear curve of uniform distribution, indicating the turning of Gaussian distribution into uniform distribution in case of severe truncation.

Similarly Laplacian assumption of the angular energy distribution can also be approached using the same analogy. A truncated Laplacian function is defined in terms of angular span as,

$$\tilde{p}_\Theta^{(L)}(\theta) = \frac{C_l}{\sqrt{2}\sigma_l} \exp \left( -\frac{\sqrt{2}|\theta - \bar{\theta}|}{\sigma_l} \right)$$  \hspace{1cm} (4.19)$$

where $\sigma_l$ is the SD of untruncated or full-span Laplacian function. $C_l$ is the normalizing constant chosen to make $\tilde{p}_\Theta^{(L)}(\theta)$ a density function. In Fig. 4.3, a truncated Laplacian density function is plotted along with a full-span or untruncated Laplacian density function. $C_l$ is given as

$$C_l = \frac{1}{1 - \exp \left( -\frac{\theta_{\text{span}}}{\sqrt{2}\sigma_l} \right)}$$  \hspace{1cm} (4.20)$$

As mentioned earlier in the Gaussian case, in equation (4.19), $\sigma_l$ also defines the pdf, $\tilde{p}_\Theta^{(L)}(\theta)$, but does not provide the correct information about the deviation of the data from the mean AoA, $\bar{\theta}$. If $\tilde{p}_\Theta^{(L)}(\theta)$ represent an untruncated Laplacian, $C_l$ becomes unity and $\sigma_\theta$ equals $\sigma_l$, otherwise $C_l$ always remains greater than 1 and $\sigma_\theta$ is less than $\sigma_l$.

Appendix 4-B provides the derivation of $\sigma_\theta$ of truncated Laplacian pdf in terms of $\sigma_l$.
and $\theta_{\text{span}}$. $\sigma_\theta$ can be written as,

$$
\sigma_\theta^2 = C_1 \sigma_l^2 - \frac{C_1 \exp\left(-\frac{\theta_{\text{span}}}{\sqrt{2\sigma_l}}\right)}{4} \exp\left(4\sigma_l^2 + \theta_{\text{span}}^2 + 2\sqrt{2}\sigma_l\theta_{\text{span}}\right)
$$

(4.21)

Fig. 4.4 shows the effect of truncation of the Laplacian function on the true SD, $\sigma_\theta$, using various values of $\sigma_l$. Fig. 4.4 provides almost similar results as discussed in the case of Fig. 4.2. However, one interesting result which can be deduced by comparing both figures is that the effect of truncation on the angle spread is more gradual in case of Laplacian than that in Gaussian, where sudden decline in $\sigma_\theta$ occurs for low values of $\theta_{\text{span}}$.

Keeping the above discussion in view, we can easily conclude that any calculations or simulations carried out for spatial correlations by using truncated Gaussian or Laplacian
models for the distribution of AoA will result in wrongful outcomes. Hence, the use of $\sigma_g$ of an untruncated Gaussian in [58] (where a truncated Gaussian is used to represent the angular energy distribution for calculating correlations among antenna elements in order to compare BER performance of a uniform circular array with that of a uniform linear array) would certainly lead to unexpected and wrongful results.

4.5 Factors which Cause Gaussian Distribution Truncation

The major factors which give rise to the situations where a Gaussian azimuthal distribution is subjected to truncate, can be categorized as follows:

**Factor 1:**

With the use of directional antenna at the base station in Gaussian scattering environment [27] one can avoid the scatterers falling out of the beam-range of antenna. This gives rise to a truncated Gaussian distribution of the AoA at the base station. In chapter 3, we have explained the effect of directional antenna at BS on the AoA distribution. In this case, the angular span $\theta_{\text{span}}$ of the AoA data will be equal to the beam width of the directional antenna, $2\alpha$, as shown in Fig. 4.5(a). This sort of situations usually belongs to the space division multiple access (SDMA) systems which rely on the use of adaptive narrow-beam
4.5 Factors which Cause Gaussian Distribution Truncation

antennas and the nonhomogeneous distribution of users in a cellular system to increase system capacity [27].

**Factor 2:**

The streets crowded with the automobile traffic represent an elliptical part of a Gaussian scattering region centered at MS. 3D angular investigations at a BS site [14] also show street canyon dominated propagation. This sort of situations have been modeled in [44]. Such elliptical scattering discs are referred to as the *Eccentro-Scattering* discs in chapter 2 of our thesis, due to the fact that the eccentricity of the disc can be altered according to the scattering structures in the street. Fig. 4.5(b) shows a scenario where a mobile is surrounded by Gaussian distributed scatterers in an elliptical disc in a crowded urban street. Usually high-rise buildings define the boundaries of scattering disc. Here the angular span depends on the major axis \(a\) and the minor axis \(b\) of the scattering disc and can be written as,

\[
\theta_{\text{span}} = 2 \tan^{-1}\left(\frac{b}{a} \tan\left(\sin^{-1}\left(\frac{a}{d}\right)\right)\right) 
\]

(4.22)

where \(d\) is the distance between BS and MS.

**Factor 3:**

In urban macrocell and microcell environment, the height of BS antenna is usually kept low, so the high-rise buildings near BS also play an important role in the dispersion of angular
4.5 Factors which Cause Gaussian Distribution Truncation

(a) Use of Directional Antenna [27], (see section 3.3)

(b) Eccentro-Scattering scenario, (see section 3.2 and 3.3)

(c) Local-to-BS scattering scenario, (see section 3.4)

(d) Far Scattering scenario [38], (see section 3.3)

Figure 4.5: The factors which cause truncation of the Gaussian distribution in AoA
4.5 Factors which Cause Gaussian Distribution Truncation

energy as seen at BS. In the measurements campaigns of both indoor [1] and outdoor [4, 56] environments, it was observed that in addition to the double exponential Laplacian (indoor case) and bell-shaped Gaussian (outdoor case), there are always very uniform tails on both sides of the mean AoA in the angular domain. The formation of these uniform tails in the distribution of AoA is in fact the aftermath of the reflections/scattering of the radio signal from the scatterers that surround BS, see Fig. 4.5(c). A detailed discussion on the issue of scattering around BS can be found in section 3.4 of this thesis, where JGSM has been proposed to model the effect of such scattering. The uniform tails cause deformation in the shape of Gaussian or Laplacian, and hence alter the measure of angle spread, i.e. the standard deviation. The angular span here mostly depend on the scatter spread around BS or in other words, the span of uniform tails. Uniform tails usually span the whole antenna beamwidth if a directional antenna of certain beamwidth (mostly 120°) is used at the base station.

Factor 4:

It has been found that the scatterer locations (or equivalently, the azimuth angles of the multipath components) are not distributed uniformly over space but tend to be concentrated in certain regions [38]. Far scatterers like high-rise buildings (in urban environments) or mountains (in rural environments) significantly contribute to the multipath scattering phenomenon in addition to the scattering structures located near the mobile stations [14, 25, 38].
4.5 Factors which Cause Gaussian Distribution Truncation

Hence, they give rise to non-symmetric and non-isotropic scattering. This kind of scattering induces a non-uniform and non-symmetric distribution in the angle of arrival (AoA) as seen at the base-station (BS). The measurement campaign conducted in [59] reveals that in some urban areas, Power Azimuthal Spectrum (PAS) exhibits a narrow peak symmetrically centered at 0° described by a truncated Laplacian curve, but also embodies an additional part centered around 8°. This additional part which breaks the symmetry of the PAS around 0°, can be considered as the aftermath of the remote or far scattering.

Far scattering gives rise to multi-modal distribution of AoA at BS, where every peak in the distribution represents a concentration center of the scattering cluster. So in such cases, the true standard deviation of the angular data differs significantly from the standard deviation of single Gaussian approximated as the distribution of AoA. We have presented a detailed study of the effect of far or distant scatterers on the azimuthal angular distribution of multipaths in chapter 3. Fig. 4.5(d) shows the situation of far scattering which gives rise to the formation of multi-modal distribution in the AoA. Here the angular span is given as,

\[ \theta_{\text{span}} \approx \sin^{-1} \left( \frac{4 \sigma_g^{(L)}}{d} \right) + \sin^{-1} \left( \frac{4 \sigma_g^{(D)}}{d_D} \right) + |\theta_D - \beta| \]  

(4.23)

where

- \( d \) is the distance between BS and MS
- \( d_D \) is the distance between BS and the center of the far scattering cluster, \( C_D \)
- \( \beta \) and \( \theta_D \) are the angles of \( d \) and \( d_D \) with some reference axis (either the axis of antenna
array or the axis of antenna broad side), and

- $\sigma_g^{(L)}$ and $\sigma_g^{(D)}$ are the standard deviations of local Gaussian scattering and far Gaussian scattering regions.

### 4.6 Angle Spread as the Goodness-of-Fit Measure in Measurement Campaigns

Many measurement campaigns [1, 4, 48, 60] have been undertaken to characterize the actual azimuthal distribution or power azimuth spectrum (PAS) in the test environment. Several analytical models have also been proposed to fit the results of such measurement campaigns in closed-form formulas, either by using Gaussian functions [4], Laplacian functions [1, 4], trigonometric functions [61] or the combinations of Gaussian and trigonometric functions [2], (also Eccentro-Scattering and JGSM models, see chapter 3). No such measure of the angular dispersion has been developed so far, on which the proximity of these models could be tested with the measurement results. Usually standard deviations, $\sigma_g$ of the Gaussian and $\sigma_l$ of the Laplacian functions are taken as the measures of angle spread to fit some specific model to measurement data, but they do not provide adequate information, especially in the cases of truncated Gaussian and Laplacian functions. On the other hand, equation (4.8) offers substantial help in this regard. It gives almost all necessary information about the angle spread, no matter what functions and how much truncation are used. We will thus exploit
4.6 Angle Spread as the Goodness-of-Fit Measure in Measurement Campaigns

Figure 4.6: Comparison of the distribution in AoA for the candidate models (Eccentro-Scattering Model [section 3.2], Gaussian [2] and Uniform Elliptical Scattering Model [3]) with the measurements [1] and simulations in indoor environments.

this measure as our goodness-of-fit criterion on good-fitting models for the two renowned measurement results presented in [1] (Indoor) and [4] (Outdoor). One very important point, which should be kept in mind while comparing the goodness-of-fit for various candidate models to the measurement data, is that the shape of the PAS or exact distribution is not so important rather the variance of the angle spread is important [62]. The same methodology can also be extended to other models assumed to fit the measurement results of various campaigns.
4.6 Angle Spread as the Goodness-of-Fit Measure in Measurement Campaigns

In indoor environments, the scatterers are usually bounded by some rigid structures, forming the boundary of the scattering region. For example, the furniture and the people in a hall represent the scattering objects while walls indicate clear boundaries to those objects. Previous research work [53] shows that in indoor environment the delay spread is usually in the range of $0.1 - 0.2 \ \mu\text{sec}$, which specifies the dimensions of the scattering area. So, exact bell-shaped Gaussian assumption either for the distribution of scatterers [2] or for the distribution of the AoA in indoor environments is usually not considered suitable (see chapter

Figure 4.7: *Comparison of the distribution in AoA for the candidate models (Eccentro-Scattering Model [section 3.2], Laplacian [1] and Raised-Laplacian) with the measurements [1] in indoor environments*
4.6 Angle Spread as the Goodness-of-Fit Measure in Measurement Campaigns

Figure 4.8: Comparison of the distribution in AoA for the candidate models (GSDM [2] and JGSM [section 3.4]) with the measurements [4] in outdoor environments

3), while the three other candidates such as the elliptical uniform scattering model [3], the Gaussian Eccentro-Scattering model and the Laplacian azimuthal distribution [1] are usually believed to be more appropriate. Using the definition of the angle spread given in (4.8), (4.18) and (4.21), we can compare all these candidate models for goodness-of-fit with the measurement data [1].

In Fig. 4.6 and 4.7, all candidate models are plotted along with their respective angle spread measures. In Fig. 4.6, we observe that the simulations (which are in fact the normalized histograms of the arrival angles as seen from the BS) and the measurements tend to form almost identical curves with a difference of $4.5^\circ$ in their angle spreads. This difference seems
4.6 Angle Spread as the Goodness-of-Fit Measure in Measurement Campaigns

to be due to the irregular shape of simulations at the tails. Gaussian Eccentro-Scattering model (section 3.2) with $\sigma_\theta = 35.7^\circ$ and uniform scattering model [3] with $\sigma_\theta = 29.5^\circ$ are observed as the best fits of first and second choices. Gaussian curves with $\sigma_\theta = 24.5^\circ$ [2] and with $\sigma_\theta = 30^\circ$ are far from goodness-of-fit in both shape and angle spread.

In Fig. 4.7, the same measurement data has been plotted along with different Laplacian functions. Laplacian functions are usually considered the best fits to model the pdf of AoA in indoor environments [1] and the PAS in outdoor environments [4]. We observe that the Laplacian function alone fails in modeling the measurements on the basis of both shape and angle spread. If $\sigma_l$ is increased to $36^\circ$, the Laplacian deviates from the measurements in the narrow stem of the measurements pdf. On the other hand, if some constant value based on the height of tails of the measurements pdf, is added to the Laplacian with $\sigma_l = 25.5^\circ$, the resultant raised Laplacian function shows good proximity to the measurements, both in shape and angle spread. Even the raised Laplacian surpasses the Eccentro-Scattering model. Actually the additional constant compensates for the effects caused by the scattering local to BS. These effects have been discussed in section 3.4 extensively.

4.6.2 Outdoor Environments

In outdoor environments, the majority of scattering points are clustered together with their density decreasing as the distance from MS increases. This fact suggests a Gaussian model for the distribution of scatterers in outdoor environments [25,27]. Measurement results for
4.7 Conclusion

the azimuthal distribution in outdoor urban environment [4] also showed a strong tendency towards Gaussian distribution. In [2], a Gaussian function with \( \sigma_g = 6^\circ \) was suggested to fit these measurements. Using (4.8), we see that \( \sigma_\theta \) of measurements is 7.1\(^\circ\), which shows 1.1\(^\circ\) discrepancy with the Gaussian. Fig. 4.8 shows that this discrepancy lies in the tails of the measurement histogram where the Gaussian function alone is not able to model the measurements. In section 3.4, formation of these tails has been discussed in the light of the aftermath of the scattering phenomenon in the vicinity of BS and Jointly Gaussian Scattering Model (JGSM) or raised Gaussian function has been suggested. In Fig. 4.8, a raised Gaussian is shown with \( \sigma_\theta = 7.2^\circ \), where a constant value based on the height of the tails of the measurement histogram is added to the Gaussian function with \( \sigma_g = 6^\circ \). We see that the resultant raised Gaussian function shows good agreement with the measurements both in shape and angle spread.

4.7 Conclusion

In this chapter, we have proposed a novel generalized method of quantifying the angle spread of the multipath power distribution. The proposed method provides almost all parameters about the angle spread, which can be further used for calculating more accurate spatial correlations of the multipath fading channels. The proposed parameters are also useful in finding the exact standard deviation of the truncated angular distributions and the angular data acquired in measurement campaigns. The degree of accuracy in correlation calculations
can lead to the computation of exact separations among array elements needed for diversity antennas. Recent use of truncated Gaussian or Laplacian functions as azimuthal distribution of multipath signals has simplified the calculation of correlations in MIMO channels. We have indicated that the use of standard deviation of full-span functions as the standard deviation of the truncated function causes severe effects on the angle spread, which in turn distorts the accuracy of correlation figures in MIMO channels. Due to the importance of angle spread in the fading statistics, we have proposed its use as the goodness-of-fit measure in measurement campaigns. The proposed method of quantifying angle spread can thus be used in finding the accurate separations among array elements in outdoor MIMO systems where measurement campaigns provide basis for channel models.

4.8 Appendix 4-A

Since the conventional definition of the standard deviation, $\sigma_\theta$, and the one given in (4.8) have the same meanings, we can use the conventional method to find the relationship between true SD, $\sigma_\theta$, of the truncated Gaussian, $\tilde{p}_\Theta(G)(\theta)$, and the SD, $\sigma_g$, of untruncated or full-span Gaussian function. The variance of the random variable, $\theta$, with the function, $\tilde{p}_\Theta(G)(\theta)$, is defined as,

$$\sigma_\theta^2 = \int_{\theta_{\min}}^{\theta_{\max}} (\theta - \bar{\theta})^2 \tilde{p}_\Theta(G)(\theta) d\theta \quad (4.24)$$
where $\bar{\theta}$ is the mean AoA defined in section 4.3. It can also be defined conventionally as,

\[ \bar{\theta} = \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} \theta \tilde{p}_{\Theta}^{(G)}(\theta) d\theta \]  \hspace{1cm} (4.25)

Using $\tilde{p}_{\Theta}^{(G)}(\theta)$ given in (4.16), and integrating with the help of tables of integrals [63], we get,

\[ \sigma_{\bar{\theta}}^2 = \frac{-C_g \sigma_g}{2\sqrt{\pi}} \left[ \sqrt{2} \left\{ (\theta_{\text{max}} - \bar{\theta}) \exp \left( -\frac{(\theta_{\text{max}} - \bar{\theta})^2}{2\sigma_g^2} \right) + \sqrt{2}(\bar{\theta} - \theta_{\text{min}}) \exp \left( -\frac{(\bar{\theta} - \theta_{\text{max}})^2}{2\sigma_g^2} \right) \right\} ight] 
- \sigma_g \sqrt{\pi} \left\{ \text{erf} \left( \frac{\theta_{\text{max}} - \bar{\theta}}{\sqrt{2} \sigma_g} \right) - \text{erf} \left( \frac{\bar{\theta} - \theta_{\text{min}}}{\sqrt{2} \sigma_g} \right) \right\} \right] \]  \hspace{1cm} (4.26)

Let the distribution, $\tilde{p}_{\Theta}^{(G)}(\theta)$, be symmetrical around mean AoA, $\bar{\theta}$ (also see Fig. 4.1), then the maximum and minimum values of the angular distribution can be written as,

\[ \theta_{\text{max}}, \theta_{\text{min}} = \bar{\theta} \pm \frac{\theta_{\text{span}}}{2} \]  \hspace{1cm} (4.27)

where $\theta_{\text{span}}$ is the angular span of the distribution, $\tilde{p}_{\Theta}^{(G)}(\theta)$. Using these minimum and maximum values in (4.26) and simplifying, we get the true variance of the truncated Gaussian distribution, $\tilde{p}_{\Theta}^{(G)}(\theta)$, as given in (4.18). It is also evident from (4.18) that the true SD does not depend on $\bar{\theta}$.

### 4.9 Appendix 4-B

A method similar to the one used in Appendix 4-A, can be exploited to derive the relationship between true SD, $\sigma_\theta$, of the truncated Laplacian, $\tilde{p}_{\Theta}^{(L)}(\theta)$, and the SD, $\sigma_t$, of untruncated or full-span Laplacian function.
The variance of the random variable, $\theta$, with the function, $\tilde{p}_\Theta^{(L)}(\theta)$, is defined as,

$$
\sigma^2_\theta = \int_{\theta_{\text{min}}}^{\theta_{\text{max}}} (\theta - \bar{\theta})^2 \tilde{p}_\Theta^{(L)}(\theta) d\theta 
$$

(4.28)

where $\bar{\theta}$ is the mean AoA defined in section 4.3 and equation (4.25). Since the truncated Laplacian $\tilde{p}_\Theta^{(L)}(\theta)$ given in (4.19) is symmetrical (also see Fig. 4.3), the true variance from $\theta_{\text{min}}$ to $\bar{\theta}$ is the same as that from $\bar{\theta}$ to $\theta_{\text{max}}$. Thus we can write (4.28) as

$$
\sigma^2_\theta = 2 \int_{\theta_{\text{min}}}^{\bar{\theta}} (\theta - \bar{\theta})^2 \tilde{p}_\Theta^{(L)}(\theta) d\theta 
$$

(4.29)

Using $\tilde{p}_\Theta^{(L)}(\theta)$ given in (4.19), and integrating with the help of tables of integrals [63], we get,

$$
\sigma^2_\theta = \frac{-C_l}{2} \left[ \sigma_l^2 \left\{ 1 - \exp \left( -\frac{\sqrt{2}}{\sigma_l} (\bar{\theta} - \theta_{\text{min}}) \right) \right\} 

- \left\{ (\bar{\theta} - \theta_{\text{min}})(\bar{\theta} - \theta_{\text{min}} - \sqrt{2}\sigma_l) \exp \left( -\frac{\sqrt{2}}{\sigma_l} (\bar{\theta} - \theta_{\text{min}}) \right) \right\} \right] 
$$

(4.30)

Assuming $\tilde{p}_\Theta^{(L)}(\theta)$ as symmetrical around $\bar{\theta}$ and substituting the value of $\theta_{\text{min}}$ from (4.27), we get $\sigma^2_\theta$ in terms of $\theta_{\text{span}}$ as given in (4.21). From (4.21), it is again evident that the true SD, $\sigma_\theta$, does not depend on $\bar{\theta}$, but it strictly depends on $\theta_{\text{span}}$. 

115
Chapter 5

Modeling Temporal Characteristics of Mobile Channel

This chapter gives a brief overview of temporal channel modeling in its section 5.1. In section 5.2, the description of the proposed temporal modeling approach is presented. Section 5.3 and 5.4 present the derivations of the closed-form formulas for the pdf of time of arrival for pico/micro and macrocell environments. In the end, section 5.5 gives the summary and final remarks of the chapter.
5.1 Overview

5.1.1 Background

Modern wireless communication systems aim to provide reliable services to as many users as possible regardless of their locations and mobility. This goal is seriously impeded by three major channel impairments, i.e. multipath, delay spread (DS), and co-channel interference (CCI). Multipath occurs in wireless communications when various incoming radio waves reach their destination (the receiver) from different directions and/or with different time delays [64]. The differences in propagation delays among these multiple propagation paths cause delay spread, which in turn induces inter-symbol interference (ISI). The time-dispersive nature of the channel determines the maximum data rate that may be transmitted without requiring equalization and also determines the accuracy of navigational services such as vehicle location [65]. Large values of DS (> 10% of the symbol duration), result in considerable degradation in system performance in terms of the attainable data rates [64]. Therefore, characterizing temporal dispersion of the channel is essential for wideband systems [66], e.g. wideband code division multiple access (WCDMA), due to strong association between DS and the inverse of signal bandwidth. Thus, it provides a measure of frequency selectivity of the channel [67]. Accurate and, if possible, simple propagation models would lead to an effective design and evaluation of modern communication systems. Such models are low-cost and handy means to accurately predict radio wave propagation behavior.
5.1 Overview

5.1.2 Problem Formulation

Early models for the multipath arrival time in urban areas date back to [68–70]. It was suggested in [68] that the sequence of path delays follows a Poisson process. But, this assumption did not fit the empirical data particularly for early arrivals and, therefore, Turin et al. [68] recommended a modified Poisson function to resolve this inconsistency (see footnote 6 in [68]). The modified Poisson function provided a better fit for the measured data as compared to the Poisson sequence [70] but it is still not good enough. In [4], the exponential decaying function has been reported as the best fit for estimated delays in outdoor environments. Indeed, the exponential function is an excellent fit to empirical data but it lacks a theoretical explanation. In [2], excellent derivation and analysis has been presented for the Gaussian Scatter Density Model (GSDM). Yet, analytical evaluation of the integral related to the probability density function (pdf) of Time of Arrival (ToA) is not permissible due to model complexity [2]. Thus, no closed-form formula for the pdf of ToA is provided for the GSDM model. In [3], a closed-form formula for the pdf of ToA has been presented for the Geometrically Based Single Bounce Macrocell (GBSBM) model, but it is valid only for a circular scattering disc. This was a limitation because in some macrocell locations, e.g. street canyon propagation [71], an elliptical scattering disc produces a more realistic propagation model, the Eccentro-Scattering model. In macrocell environments, distant scatterers far from Base Station (BS) and Mobile Station (MS) have considerable effect on the received signal. However, few scattering models acquiesced the effect of distant scatterers on the
5.1 Overview

multipath signal. The model in [72] predicts the power of reflected paths from distant reflectors with no consideration of spatial or temporal aspects of the received signal. In chapter 3, a model for the spatial statistics of cellular environments including the effect of distant scatterers has been presented. So far, no scattering model incorporated the effect of distant scatterers on the temporal dispersion of the multipath signal in macrocell environments.

5.1.3 Contributions

In this chapter, we derive simplified closed-form expressions for the ToA distributions for picocell/microcell and macrocell environments by considering the scatterers confined in Eccentro-Scattering discs. This is a more general approach from which the results of the previous models, such as GBSBM [3], can be deduced as its special cases. For macrocell environments, we also include the effect of dominant distant scatterers on the temporal dispersion of the multipath signals. Objects such as hills, mountains, and skyscrapers act as clustered scatterers/reflectors when they have line of sight (LoS) to both BS and MS [16, 25]. The derived formulas can be used to simulate temporal dispersion of wireless signal in several propagation conditions. The pdf of ToA is very important for finding the covariance of two multipath signals as a function of their frequency separation. Covariance of two multipath signals is in fact the characteristic function of the pdf of time delays [22]. Besides the handy use of the pdf of ToA in determining the coherence bandwidth of a particular system, it also emerges as a basic characteristic of the system capacity along with the pdf of AoA [22]. The
pdf of AoA has been discussed in detail in chapter 3. Almost complete description of the wireless system can be achieved if the pdfs of time and angle of arrival are known.

In this chapter, we also present formulas for the areas of intersection between two elliptical regions and between a circle and an ellipse. These formulas are necessary for the derivation of the pdf of ToA and can also be used in other mathematical applications.

5.2 Model Description

Multiple replicas of the transmitted signal are received at the receiver due to the multipath propagation in the radio environment. These multipath components of the received signal arrive at the receiver antenna with identical or different delays [22, 23, 49]. The distribution of these multipath components in time-delay is conveniently described by the function \( p(\tau) \), where \( \tau \) is the delay of the multipath component in time domain. Thus, a specific signal delay \( \tau \) defines a set of scatterers bounded by an elliptical region, with foci BS and MS and distinct major and minor axes. This ellipse will be referred to as the ‘bounding ellipse’ in our work. Such a bounding ellipse has been shown in Fig. 5.1. The scatterers on the boundary of the bounding ellipse give rise to single bounce multipath components [24, 51]. Therefore, different delays correspond to different confocal ellipses [13], with BS and MS as common focal points.

Based on the assumptions given in chapter 2, an \( n \)th bounding ellipse defines a specific
5.2 Model Description

Figure 5.1: Geometry of the proposed temporal channel model

Figure 5.2: Temporal model for a typical multipath fading environment
5.2 Model Description

set of scatterers that gives rise to multipath components arriving between time delays $\tau_n$ and $\tau_{n+1} = \tau_n + \delta \tau$. This phenomenon is explained in Fig. 5.2, where different sets of scatterers are giving rise to the formation of different confocal bounding ellipses.

Consider an $n$th bounding ellipse centered at $C$ with foci $B$ (BS) and $M$ (MS) separated by a distance $d$ and with semi-major and semi-minor axes $a_{\tau_n}$ and $b_{\tau_n}$ respectively, as shown in Fig. 5.1. $r_{BS}$ and $r_{MS}$ satisfy,

$$r_{BS} + r_{MS} = 2a_{\tau_n} \quad (5.1)$$

Eccentricity of this bounding ellipse is defined as,

$$e_{\tau_n} = \sqrt{1 - \kappa_{\tau_n}^2} \quad (5.2)$$

where $\kappa_{\tau_n}$ is the aspect ratio of the bounding ellipse and equals $b_{\tau_n}/a_{\tau_n}$. Eccentricity of the bounding ellipse can also be defined in terms of the MS-BS separation and the major axis as,

$$e_{\tau_n} = \frac{d}{2a_{\tau_n}} \quad (5.3)$$

Using radio signal propagation theory, the relationship among time delay $\tau_n$, path travelled by the multipath signal, $r_{BS} + r_{MS}$, and speed of light $c$ can be written as,

$$r_{BS} + r_{MS} = c\tau_n \quad (5.4)$$

Let a specific time delay $\tau_n$ define a set of scatterers bounded by $n$th bounding ellipse. Then the semi-major axis $a_{\tau_n}$ and semi-minor axis $b_{\tau_n}$ of the $n$th bounding ellipse can be
In our work, we will denote the semi-major axis and eccentricity of the outermost bounding ellipse by the notations $a_{\tau_{\text{max}}}$ and $e_{\tau_{\text{max}}}$, respectively. Both variables are related to the maximum delay spread, $\tau_{\text{max}}$. Use of $a_{\tau_n}$ should not be confused with the notation $a$ in chapters 2 and 3, where $a$ denotes the semi-major axis of a fixed Eccentro-Scattering disc in a spatial channel model. However, $a_{\tau_{\text{max}}}$ and $e_{\tau_{\text{max}}}$ are equivalent to $a$ and $e$ of the Eccentro-Scattering spatial channel model in the case of picocell and microcell environments, but not equivalent to $a$ and $e$ of the Eccentro-Scattering spatial channel model in macrocell environment. This is due to the fact that $a$ and $e$ of the Eccentro-Scattering disc in case of picocell and microcell environments depend on $\tau_{\text{max}}$, while being independent of $\tau_{\text{max}}$ in macrocell environment, they depend only on the terrain and orientation of the streets, roads or valleys.

In order to find the pdf of ToA, we will first find the cumulative distribution function (CDF) of ToA, which may be calculated as the probability of a scatterer being placed inside the $n$th bounding ellipse corresponding to time delay $\tau_n$. Thus,

$$P_\tau(\tau_n) = \frac{A_{\tau_n}(\tau_n)}{A}$$

where $A_{\tau_n}(\tau_n)$ is the area of overlap between the $n$th bounding ellipse corresponding to time delay $\tau_n$ and the Eccentro-Scattering disc (pico/micro or macro) and $A$ is the area of the
whole Eccentro-Scattering disc. Then, the pdf of ToA would be the derivative of the CDF with respect to $\tau_n$. Thus,

$$p_{\tau_n}(\tau_n) = \frac{d}{d\tau_n}P_{\tau_n}(\tau_n) = \frac{1}{A} \frac{d}{d\tau_n}A_{\tau_n}(\tau_n)$$  \hspace{1cm} (5.8)

### 5.3 pdf of ToA for Picocells and Microcells

In this section, we derive the pdf of ToA of the multipaths for picocell and microcell environments. In such environments, BS and MS are located closer to each other and both have scatterers around them. The antenna heights are relatively low and multipath scattering is assumed near both BS and MS. Therefore, BS and MS are located at the focal points of the Eccentro-Scattering disc. It was explained earlier that BS and MS are the common focal points for all bounding ellipses. So, the pico/micro Eccentro-Scattering disc encloses all bounding ellipses such that the bounding ellipse corresponding to the maximum allowed delay, $\tau_{\text{max}}$, coincides the pico/micro Eccentro-Scattering disc. Thus,

$$\tau_{\text{max}} = \frac{2a\tau_{\text{max}}}{c} = \frac{2a}{c}$$  \hspace{1cm} (5.9)

Fig. 5.3 represents the scattering model for picocell and microcell environments. In the figure, $C$ is the common center of all bounding ellipses and the pico/micro Eccentro-Scattering disc; and $B$ (BS) and $M$ (MS) are their common focal points. $a$ and $b$ are the semi-major and semi-minor axes of the pico/micro Eccentro-Scattering disc.

For the $n$th bounding ellipse corresponding to the time delay $\tau_n$ in the case of picocells and
microcells, the following parameters are defined,

\[
a_{\tau_n} = \frac{c\tau_n}{2} \quad (5.10)
\]
\[
b_{\tau_n} = \frac{1}{2} \sqrt{4a_{\tau_n}^2 - d^2} \quad (5.11)
\]
\[
e_{\tau_n} = \frac{d}{c\tau_n} \quad (5.12)
\]

The area of the pico/micro Eccentro-Scattering disc in Fig. 5.3, \( A \), is defined as,

\[
A = \pi ab
\]
\[
= \pi a_{\tau_{\text{max}}} b_{\tau_{\text{max}}} \quad (5.13)
\]

Therefore, the area of overlap between the \( n \)th bounding ellipse corresponding to time delay, \( \tau_n \), and the pico/micro Eccentro-Scattering disc will be equal to the whole area bounded by that bounding ellipse, i.e.,

\[
A_{\tau_n}(\tau_n) = \pi a_{\tau_n} b_{\tau_n}
\]
\[
= \frac{\pi c\tau_n}{4} \sqrt{c^2\tau_n^2 - d^2} \quad (5.14)
\]
Substituting (5.13) and (5.14) into (5.8), we get the pdf of ToA for picocell and microcell environments as follows [3],

\[
p_r(\tau_n) = \begin{cases} 
\frac{c(2c^2\tau_n^2 - d^2 - 4a^2e^2)}{4a^2\sqrt{1 - e^2\sqrt{c^2\tau_n^2 - 4a^2e^2}}}, & \tau_0 < \tau_n < \tau_{\text{max}} \\
0, & \text{elsewhere}
\end{cases}
\]  

(5.15)

where \( e \) is a constant representing the eccentricity of the pico/micro Eccentro-Scattering disc, defined as \( e = d/(2a) \) and \( \tau_0 \) is a constant representing the delay of the first multipath arrival or usually delay in LoS path, defined as \( \tau_0 = d/c \). Equation (5.15) can also be written as,

\[
p_r(\tau_n) = \begin{cases} 
\frac{\tau_n(2 - e^2\tau_n^2)}{\tau_{\text{max}}^2\sqrt{1 - e^2\sqrt{1 - e^2\tau_n^2}}}, & \tau_0 < \tau_n < \tau_{\text{max}} \\
0, & \text{elsewhere}
\end{cases}
\]  

(5.16)

where \( e_{\tau_n} \) is a variable representing the eccentricity of the \( n \)th bounding ellipse, which corresponds to the time delay \( \tau_n \) and is defined as \( e_{\tau_n} = d/(c\tau_n) \).

Fig. 5.4 illustrates the effect of changing the value of the semi-major axis of the pico/micro Eccentro-Scattering ellipse, \( a \), or the distance between BS and MS, \( d \), on the pdf of ToA in picocells and microcells. In Fig. 5.4(a), we keep the distance between BS and MS fixed at the value, \( d = 12 \) m, and change the value of the major axis of the Eccentro-Scattering ellipse, \( a \), consequently \( e \) and \( \tau_{\text{max}} \) change. Since \( d \) is fixed, then the delay of the LoS, \( \tau_0 \), is also fixed. Therefore, an increase in the value of the semi-major axis of the Eccentro-Scattering ellipse, \( a \), would result in an increase in the value of the maximum delay, \( \tau_{\text{max}} \), thus the temporal spread increases. This is the case when an increase in the number of scatterers influences the multipath signal. Conversely, small values of the temporal spread correspond to situations when only small numbers of scatterers influence the multipath signal, those influential scat-
Figure 5.4: pdf of ToA for picocell and microcell environments
scatterers exist around the direction of LoS thus the scattering ellipse (the Eccentro-Scattering disc) gets higher values for its eccentricity.

Fig. 5.4(b) illustrates the effect of changing the distance between BS and MS, $d$, on the temporal spread of the multipath signal. We choose a fixed value for the semi-major axis of the pico/micro Eccentro-Scattering disc, $a = 8$ m, and change the distance between BS and MS, $d$. Consequently, the eccentricity of the pico/micro Eccentro-Scattering disc, $e$, and $\tau_0$ change. Since $a$ is fixed, then the maximum delay, $\tau_{\text{max}}$, is also fixed. Therefore, an eccentricity value close to 0 implies that MS is in the neighborhood of BS, so the delay of the first multipath signal (or the delay in the LoS) is small and, hence, the temporal spread is large. Whereas, an eccentricity value close to 1, indicates MS is far from BS, so the delay of the first multipath signal (or the delay in the LoS) is large, i.e. $\tau_0$ approaches $\tau_{\text{max}}$, and, thus, the temporal spread would be small. Before $e$ becomes 1, MS should be handed over to a new BS in order to guarantee uninterrupted coverage. For more discussion on this issue refer to the section 4 of chapter 6.

5.4 pdf Of ToA for Macrocells

In macrocell environments, several local and distant scatterers contribute to the multipath signal as shown in Fig. 5.2.

Here, BS is usually far away from MS, i.e. the distance between BS and MS is in the
order of kilometers and BS is typically positioned higher than the surrounding scatterers, i.e. more than 30 meters above ground [14]. Therefore, BS is located outside the scattering ellipse, i.e. no scatterers are assumed around BS, and MS is located at its center. In [73], a scattering model has been presented in which BS is assumed to be at the center of the scattering area and MS is somewhere at the edge. This is an impractical assumption based on numerous empirical and theoretical results. In macrocells, less, or no, scatterers exist in the vicinity of BS. The scattering maps measured during the trials confirm that in many cases the significant scattering from a mobile in the field is constrained to an area centered on the mobile [54].

Due to the far distance separating BS and MS, the multipath signal is also influenced by objects far from transmitter and receiver. Objects such as hills, mountains, and skyscrapers act as clustered scatterers when they have LoS to both BS and MS [25]. Therefore, signals reflected from these structures arrive at the receiver as clusters in space and time. The effect of distant scatterers is apparent in suburban and hilly areas. In bad urban environment, a two-cluster model is more appropriate [14], where distant scatterers are usually the high-rise buildings. Therefore, our model encompasses a distant scattering disc in addition to the local scattering ellipse in suburban and hilly areas. For simplicity of the derivation, we will derive the pdf of ToA for macrocells in two parts; first due to local scatterers around MS and second due to the dominant distant scatterers.
Figure 5.5: Temporal channel model for macrocells
5.4 pdf Of ToA for Macrocells

5.4.1 Local Scatterers

The proposed scattering model for local scatterers in macrocell environment is depicted Fig. 5.5(a). In the figure, C, B (BS), and M (MS) are the center and two focal points of the bounding ellipse corresponding to time delay $\tau_n$ with semi-major and semi-minor axes $a_{\tau_n}$ and $b_{\tau_n}$, respectively. The local scattering ellipse is centered at M with semi-major and semi-minor axes $a$ and $b$, respectively. The location of a scattering point on the bounding ellipse corresponding to time delay $\tau_n$, $L_{\tau_n}$, from M is defined by $(r_{\tau_n}, \phi)$, whereas the location of a scattering point on the local scattering ellipse, $L_s$, from M is defined by $(r_s, \phi)$. The bounding ellipse corresponding to $\tau_n$ and the scattering ellipse intersect at $L_x$, which is located at angle $\alpha_1$ as shown in Fig. 5.5(a). The equation defining the bounding ellipse corresponding to delay $\tau_n$ in Fig. 5.5(a) is,

$$
\left(\frac{r_{\tau_n} \cos \phi - d/2}{a_{\tau_n}^2}\right)^2 + \frac{r_{\tau_n}^2 \sin^2 \phi}{b_{\tau_n}^2} = 1 \tag{5.17}
$$

Solving 5.17, $r_{\tau_n}$ can be found as,

$$
r_{\tau_n} = \frac{4a_{\tau_n}^2 - d^2}{2(2a_{\tau_n}^2 - d \cos \phi)} = \frac{c^2 r_{\tau_n}^2 - d^2}{2(c r_{\tau_n} - d \cos \phi)} \tag{5.18}
$$

The equation defining the Macro Eccentro-Scattering ellipse in Fig. 5.5(a) is,

$$
\frac{r_s^2 \cos^2 \phi}{a^2} + \frac{r_s^2 \sin^2 \phi}{b^2} = 1 \tag{5.19}
$$

Solving 5.19, $r_s$ can be found as,

$$
r_s = \frac{a^2 b^2}{\sqrt{a_s^2 \sin^2 \phi + b^2 \cos^2 \phi}} \tag{5.20}
$$
Here, an important part of the derivation is to find the area of overlap between the bounding and the scattering ellipses. Referring to Fig. 5.5(a), the area of overlap between the bounding ellipse corresponding to delay $\tau_n$ and the scattering ellipse, $A_1(\tau_n)$, can be calculated using the following integral,

$$A_1(\tau_n) = \int_0^{\alpha_1} r_s^2(\phi) d\phi + \int_{\alpha_1}^{\pi} r_{\tau_n}^2(\phi) d\phi$$  \hspace{1cm} (5.21)$$

Since $\alpha_1$ equals $\phi$, when $r_{\tau_n} = r_s$; equating (5.18) and (5.20) and solving for $\phi$, we get

$$\alpha_1 = \cos^{-1}(f_1)$$  \hspace{1cm} (5.22)$$

where

$$f_1 = \frac{4a^2\kappa^2 c\tau d + \sqrt{f_2(d^2 - c^2\tau^2)}}{f_3}$$  \hspace{1cm} (5.23)$$

$$f_2 = e^2(c^2\tau^2 - d^2)^2 + 4a^2\kappa^2(d^2 - e^2c^2\tau^2)$$  \hspace{1cm} (5.24)$$

$$f_3 = e^2(c^2\tau^2 - d^2)^2 + 4a^2\kappa^2d^2$$  \hspace{1cm} (5.25)$$

and $\kappa$ and $e$ are, respectively, the aspect ratio and eccentricity of the Macro Eccentric Scattering disc.

After carrying out the required mathematical manipulations and parameter substitutions in (5.21), we get the area of the overlapping region between the bounding ellipse corresponding to delay $\tau_n$ and the scattering ellipse in Fig. 5.5(a), $A_1(\tau_n)$, as follows,

$$A_1(\tau_n) = a^2\kappa\tan^{-1}\left(\frac{\tan \alpha_1}{\kappa}\right) + \frac{c^2\tau^2(e_{\tau_n}^2 - 1)}{4} \left\{ \frac{-\pi}{\sqrt{1-e_{\tau_n}^2}} + \frac{e_{\tau_n}\sin \alpha_1}{1-e_{\tau_n}\cos \alpha_1} + \frac{2}{\sqrt{1-e_{\tau_n}^2}}\tan^{-1}\left(\frac{\sqrt{1+e_{\tau_n}}\tan(\alpha/2)}{\sqrt{1-e_{\tau_n}}}\right) \right\}$$  \hspace{1cm} (5.26)$$
5.4 pdf Of ToA for Macrocells

Substituting $A = \pi ab$ and $A_1(\tau_n)$ from (5.26) into (5.8), we get the pdf of ToA for macrocell environment due to local scattering disc as follows,

$$p_\tau(\tau_n) = \begin{cases} \frac{1}{\pi a^2 \kappa} \left( f_5 - \frac{a^2 \kappa^2 f_4}{(1 - e^2 f_1^2)\sqrt{1 - f_1^2}} \right), & \tau_0 < \tau_n < \tau_{\max} \\ 0, & \text{elsewhere} \end{cases}$$  \quad (5.27)

where,

$$f_4 = \frac{1}{f_3\sqrt{f_2}} \left\{ 4a^2 \kappa^2 cd\sqrt{f_2} - 2f_2 c^2 e^2 \tau_n (d^2 - c^2 \tau_n^2)(d^2 - c^2 \tau_n^2 + 2a^2 \kappa^2) \right\} + \frac{1}{f_3^2} \left( 16a^2 \kappa^2 e^2 c^2 \tau_n^2 d(d^2 - c^2 \tau_n^2) + 4c^2 e^2 \tau_n (d^2 - c^2 \tau_n^2)^2 \sqrt{f_2} \right)$$  \quad (5.28)

$$f_5 = \frac{c(2c^2 \tau_n^2 - d^2)}{2\sqrt{c^2 \tau_n^2 - d^2}} \left\{ \frac{\pi}{2} - \tan^{-1} \frac{(c\tau_n + d)(1 - f_1)}{(c\tau_n - d)(1 + f_1)} \right\} + \frac{cd^2 (c\tau_n f_1 - d) \sqrt{1 - f_1^2}}{4(c\tau_n - df_1)^2} + \frac{(c^2 \tau_n^2 - d^2)^2 f_4}{4(c\tau_n - df_1)^2 \sqrt{1 - f_1^2}}$$  \quad (5.29)

$$\tau_{\max} = \frac{d + 2a}{c}$$  \quad (5.30)

Assuming circular scattering disc around MS, i.e. $a = b = R$, as in GBSBM [3] is a special case of our work. So, a simplified version of the pdf of ToA formula in [3] would be,

$$p_\tau(\tau_n) = \begin{cases} \frac{c(2c^2 \tau_n^2 - d^2)}{2\pi R^2 \sqrt{c^2 \tau_n^2 - d^2}} \left\{ \frac{\pi}{2} - \tan^{-1} \frac{(c\tau_n + d - 2R)(1 + f_1)}{(c\tau_n + d + 2R)(1 - f_1)} \right\} + \frac{(2R - c\tau_n) \sqrt{d^2 - (c\tau_n - 2R)^2}}{2(2c^2 \tau_n^2 - d^2)}, & \tau_0 < \tau_n \leq \tau_{\max} \\ 0, & \text{elsewhere} \end{cases}$$  \quad (5.31)
5.4 pdf Of ToA for Macrocells

5.4.2 Distant Scatterers

In Fig. 5.5(b), the proposed scattering model for dominant distant scatterers in macrocell environment is illustrated. In the figure, C, B (BS), and M (MS) are the center and focal points of the bounding ellipse corresponding to delay $\tau_n$ with semi-major and semi-minor axes $a_{\tau_n}$ and $b_{\tau_n}$, respectively. The following distances are defined; $d_{BO} = |BO|$, $d_{OM} = |OM|$, $r_{BL} = |BL_D|$, and $r_{ML} = |LM|$. O is the center of the Distant Eccentro-Scattering disc located at the point $(d_{BO}, \theta_D)$ with semi-major and semi-minor axes $a_D$ and $b_D$, respectively. The location of any scattering point, $L_D$, on the distant Eccentro-Scattering disc with respect to $B$ is defined as $(r_{BL}, \theta)$ and with respect to $M$ is defined as $(r_{ML}, \phi)$.

The distant scattering disc intersects with the bounding ellipse corresponding to delay $\tau_n$ at $(x_1, y_1)$ and $(x_2, y_2)$ as shown in Fig. 5.5(b).

The bounding ellipse corresponding to delay $\tau_n$ in Fig. 5.5(b) is defined in (5.17); we can re-write it in Cartesian coordinates as,

$$y_{\tau_n} = \sqrt{\frac{c^2}{c\tau_n} - d^2} \sqrt{\frac{c^2\tau_n^2}{4} - \left(x_{\tau_n} - \frac{d}{2}\right)}$$

The distant Eccentro-Scattering disc in Fig. 5.5(b) is defined as,

$$y_D = d_{BO} \sin \theta_D - \kappa_D \sqrt{\frac{a_D^2}{4} - (x_D - d_{BO} \cos \theta_D)^2}$$

Here also, an important part of the derivation is to find the area of overlap between the bounding ellipse corresponding to delay $\tau_n$ and the distant Eccentro-Scattering disc. To find the area of intersection, we need to find the abscissas of the two points of intersection,
5.4 pdf Of ToA for Macrocells

$x_1$ and $x_2$ in Fig. 5.5(b). Therefore, equating (5.32) and (5.33), we obtain the two solutions for $x$. Alternatively, to simplify the derivation, we will assume that distant scatterers are confined within a circular scattering disc with radius $R_D$. The general case of elliptical distant scattering disc can be handled similarly; although huge expressions will be required.

We adopt the following simplified equation for a circular distant scattering disc,

$$y_D = \frac{d}{2} \tan \theta_D - \sqrt{R_D^2 - (x_D - d/2)^2}$$

(5.34)

Solving (5.32) and (5.34) simultaneously for $x = x_{\tau_n} = x_D$, we get the following two real solutions,

$$x_{1,2} = \frac{1}{2d} (d^2 + c\tau_n f_6)$$

(5.35)

where,

$$f_6 = \sqrt{c^2 \tau_n^2 + 4R_D^2 + (d^2 - 2c^2 \tau_n^2) \sec^2 \theta_D + 2 \tan \theta_D \sqrt{d^2 - c^2 \tau_n^2} (4R_D^2 - c^2 \tau_n^2 \sec^2 \theta_D)}$$

(5.36)

From (5.32) and (5.34), the area of intersection, $A_2(\tau_n)$, would be,

$$A_2(\tau_n) = \int_{x_1}^{x_2} (y_{\tau_n}(x) - y_D(x)) \, dx$$

(5.37)

Equation (5.37) can be simplified to,

$$A_2(\tau_n) = \frac{c\tau_n f_6}{4d^2} \left[ \sqrt{4R_D^2 d^2 - c^2 \tau_n^2 f_6^2} \sqrt{c^2 \tau_n^2 - d^2} \left( d - f_6 \right) \right]$$

$$+ \frac{c\tau_n}{4} \sqrt{c^2 \tau_n^2 - d^2 \sin^{-1} \left( \frac{f_6}{d} \right)} + R_D \sin^{-1} \left( \frac{c\tau_n f_6}{2R_D d} \right) - \frac{c\tau_n f_6}{2} \tan \theta_D$$

(5.38)

Substituting, $A = \pi R_D^2$, and the value of $A_2(\tau_n)$ from (5.38) in (5.8), we get the pdf of ToA
Figure 5.6: pdf of ToA for macrocells with the effect of distant scatterers

due to circular distant scattering disc as,

$$p_r(\tau_n) = \frac{1}{2\pi R_D^2 d^2} \left\{ c(f_6 + \tau_n f_7) \left( \sqrt{4R_D^2 d^2 - c^2\tau_n^2 f_6^2 - d^2 \tan \theta_D} \right) + c\tau_n f_7 \sqrt{(c^2\tau_n^2 - d^2)(d^2 - f_6^2)} \right. $$

$$\left. + \frac{c(2c^2\tau_n^2 - d^2)}{2\sqrt{c^2\tau_n^2 - d^2}} \left( f_6 \sqrt{d^2 - f_6^2} + d^2 \sin^{-1} \left( \frac{f_6}{d} \right) \right) \right\}$$

Equation (5.39) is valid for $\tau_{\min} < \tau_n \leq \tau_{\max}$, where $\tau_{\max}$ and $\tau_{\min}$ are defined as,

$$\tau_{\max}, \tau_{\min} = \frac{2}{c} \sqrt{d^2 + \left( \frac{d}{2} \tan \theta_D \pm R_D \right)^2}$$

The pdf of ToA due to local scatterers is given in (5.27) and the pdf of ToA due to distant scatterers is given in (5.39). However, it should be noted that each of these two formulas
5.5 Conclusions

has to be applied over the corresponding region and the pdf of ToA is assumed to be zero outside these regions. Nevertheless, when the two regions overlap, the resultant pdf of ToA would then be the normalized sum of (5.27) and (5.39) over the common region, see Fig. 5.6. The following model parameters were used in the simulation: $d = 1000 \, m$, $a = 500 \, m$, $e = 0.5$, $\theta_D = 63.4^\circ$, and $R_D = 600 \, m$. In several macrocell environments, e.g. hilly and bad urban, a scattering model should consist of the distant scattering disc in addition to local scattering disc, in order to imitate the physical scattering behavior more pragmatically. Hence, Fig. 5.6 signifies the importance of the proposed model as it incorporates the effect of distant scatterers in addition to that of local scatterers.

5.5 Conclusions

In this chapter, we have discussed the temporal characteristics of cellular mobile channel in picocell, microcell, and macrocell environments. We have employed the proposed Eccentro-Scattering model to derive the pdf of ToA of the multipath signal for these cellular environments. In macrocell environment, our model incorporated the effect of distant scatterers, far from BS and MS on the temporal dispersion of the multipath signal in addition to that of local scatterers. A simplified generic closed-form formula for the pdf of ToA due to local scatterers has been derived from which previous models can be easily reproduced. For distant scatterers, a circular scattering disc has been adopted; nevertheless the same methodology can be used for an elliptical scattering disc or an Eccentro-Scattering disc.
The presented formulas can be used to simulate temporal dispersion of the multipath channel in a variety of propagation conditions. Furthermore, these formulas are also helpful in designing efficient equalizers to combat intersymbol interference (ISI) for frequency-selective fading channels.
Chapter 6

Effect of Mobile Motion on the Spatio-Temporal Characteristics

In section 6.1 of this chapter, an overview of the previous work and chapter contributions are presented. Section 6.2 describes the three MS motion scenarios which affect the spatial and temporal statistics of the channel. In section 6.3, the important spatial parameters are described, and the behavior of these parameters under MS motion is discussed in detail. Section 6.4 presents the description of important temporal parameters and discusses their behavior under MS motion. Finally, section 6.5, concludes the chapter and presents final remarks.
6.1 Overview

Propagation models are usually considered low-cost and handy means of predicting accurate radio wave propagation behavior. In order to enhance capacity, efficient exploitation of radio channel resources [5, 14] is required. Conventional physical channel models can be considered as stationary models, since they exclude the effects of motion on the channel characteristics. Recently, very good work has been presented to provide dynamic channel models by considering the motion of mobile station and/or scatterers [25, 74–79]. In [14], measurements have been presented for the elevated BS-antenna systems (rural environments), which show inconsistent behavior of the angle spread when an increase occurs in MS-BS separation. However, no explanatory model has been proposed so far to explain the behavior of spatio-temporal statistical parameters of the multipath fading channel under the effect of the displacement of MS or BS. This motivated us to analyze the spatial and temporal statistics of mobile radio channel and investigate their behavior under mobile motion.

The main contributions of this chapter may thus be summarized as follows:

1. We consider a realistic situation of a moving MS for the characterization of multipath fading channel and investigate how this motion affects the spatio-temporal characteristics at BS.

2. We present three mobile motion scenarios that are responsible for the alterations in the spatio-temporal characteristics and plot the behavior of various spatial and temporal
spread quantifiers during these motion scenarios. We also explain the behavior of angle spread under the effect of mobile motion, observed in the field measurements [14]. We show that the model successfully simulates the time-variability of the angle and delay spreads induced during the course of MS motion.

3. We identify two different cases when the terrain and clutter of MS surroundings have an additional effect on the temporal spread of the channel during MS motion. These cases can provide good basis for the performance evaluation in those wireless systems which employ additional time-delay processing techniques.

6.2 Mobile Motion Scenarios

As we have already discussed in chapter 2 that the multipath components of a received signal arrive at the receiver antenna from different azimuth directions about the horizon with identical or different delays. The distributions of these multipath components in the azimuth and time are conveniently described by the functions $p(\theta)$ and $p(\tau)$, where $\theta$ is the azimuthal AoA and $\tau$ is the delay of the multipath component in time domain. The work in this chapter is based on the general assumptions made in chapter 2. Moreover, we assume uniformly distributed scatterers in the scattering region. However, the same methodology can also be extended to the case of Gaussian distributed scatterers.

Let MS moves from position $P_i$ to position $P_{i+1}$ with velocity $v$ and angle $\phi_v$ with $x$-axis
and traverses a small distance $\delta_d$ such that $\delta_d \to 0$, in an infinitesimal small time interval $\delta_t$ in the direction of $v$, see Fig. 6.1. It can be shown that

$$\delta_d = v \delta_t$$  \hspace{1cm} (6.1)

This change in the displacement causes a change in the whole scattering environment around MS. If we use subscripts $i$ and $i + 1$ to represent the values of various scattering variables at positions $P_i$ and $P_{i+1}$, respectively, then we can write the general expression for the next state of MS-BS separation in terms of previous state as

$$d_{i+1} = \sqrt{d_i^2 + 2 \delta_d d_i \cos(\beta - \phi_v) + \delta_d^2}$$  \hspace{1cm} (6.2)

The above change in the MS-BS separation strictly depends on $v$ and $\phi_v$, because $v$ and $\phi_v$ collectively define MS motion. Especially $\phi_v$ forces the MS-BS separation either to undergo speedy change or keep constant. We thus consider three possible trajectories of MS with
respect to BS position as shown in Fig. 6.1. The motion scenarios which give rise to these trajectories are as follows:

**Scenario 1:** MS is moving along the direction of LoS towards or away from BS. In this case \( \phi_v \) equals \( \beta \) and both do not change during MS motion. Obviously, the distance between BS and MS will change linearly.

**Scenario 2:** MS is moving in a circular path around BS. In this case, both \( \phi_v \) and \( \beta \) change at each instant of time and \( \phi_v \) is equal to \( \beta + \delta \beta + \pi/2 \) during MS motion, where \( \delta \beta \) is an infinitesimally small interval such that \( \delta \beta \to 0 \), Fig. 6.1. Due to circular motion of MS around BS, the distance between BS and MS remains constant.

**Scenario 3:** MS is neither moving along the direction of LoS nor in a circular path with respect to BS. This is the general case. Here, \( \phi_v \) is assumed to be constant during MS motion for a certain specified period of time depending on the rate of data processing. \( \beta \) and the distance between BS and MS change at each instant of time, see Fig. 6.1. Note, the change in \( \beta \) is infinitesimally small.
6.3 Behavior of Spatial Characteristics under Mobile Motion

6.3.1 Important Spatial Parameters

In this section, we revisit some of the important spatial parameters already defined and explained in chapter 4.

**Angular span, \( \theta_{\text{span}} \):** This is the total width of the AoA distribution, \( p(\theta) \), on the angular domain. It can be written as,

\[
\theta_{\text{span}} = \theta_{\text{max}} - \theta_{\text{min}}
\]  
(6.3)

where \( \theta_{\text{max}} \) and \( \theta_{\text{min}} \) are the maximum and minimum angles of arrival, respectively.

**Circular Variance, \( S_0 \):** It is the basic measure of the dispersion of the multipath signals in space. It is defined as,

\[
S_0 = 1 - |\bar{R}_1|
\]  
(6.4)

where \( \bar{R}_1 = \bar{C}_1 + j\bar{S}_1 \) is the first complex trigonometric moment of \( p(\theta) \). The trigonometric parameters \( \bar{C}_1 \) and \( \bar{S}_1 \) are defined as follows,

\[
\bar{C}_1 = \frac{1}{P_0} \int_0^{2\pi} p(\theta) \cos(\theta) d\theta
\]  
(6.5)

and

\[
\bar{S}_1 = \frac{1}{P_0} \int_0^{2\pi} p(\theta) \sin(\theta) d\theta
\]  
(6.6)
6.3 Behavior of Spatial Characteristics under Mobile Motion

where \( P_0 = \int_0^{2\pi} p(\theta) d\theta \).

As we have discussed in detail in section 4.3 that \( S_0 \) is invariant under the changes in transmitted power, and any series of rotational or reflective transformation of \( p(\theta) \).

We see that \( 0 \leq S_0 \leq 1 \), which means that the observed AoAs are tightly clustered about the mean direction \( \theta \); then, \(|\bar{R}_1|\) will be closer to 1 and \( S_0 \) will be nearly zero.

On the other hand, if the AoAs are widely dispersed then \(|\bar{R}_1|\) will be small and \( S_0 \) will be nearly 1.

Mean Angle of Arrival, \( \bar{\theta} \): It can also be referred to as the mean direction of the first complex trigonometric moment, \( \bar{R}_1 \), and is written as,

\[
\bar{\theta} = \tan^{-1} \left( \frac{\bar{S}_1}{\bar{C}_1} \right)
\] (6.7)

Angle Spread Shape Factor, \( \Lambda \): It is another measure of the azimuthal dispersion of the multipath signals, used by Durgin et al. in [32]. It is closely related to the circular variance and the first trigonometric moment proposed in in section 4.3 as,

\[
\Lambda = \sqrt{1 - |\bar{R}_1|^2} = \sqrt{2S_0 - S_0^2}
\] (6.8)

Standard Deviation of the AoA, \( \sigma_\theta \): Conventionally it is the square root of the second central moment of \( p(\theta) \).

\[
\sigma_\theta = \sqrt{\int_0^{2\pi} (\theta - \bar{\theta})^2 p(\theta) d\theta}
\] (6.9)
It can easily be written in terms of $S_0$ and $\bar{R}_1$ as,

\[
\sigma_\theta = \sqrt{-2 \ln(1 - S_0)} \\
= \sqrt{-2 \ln(|\bar{R}_1|)}
\]  

(6.10)

It is the most important spatial parameter and provides the true physical information about the angular dispersion of the data in radians.
6.3 Behavior of Spatial Characteristics under Mobile Motion

6.3.2 Effect of Mobile Motion on the Spatial Characteristics of the Channel

6.3.2.1 Picocell and Microcell Environments

In microcell and picocell environments, BS and MS are located close to each other and both have scatterers in their vicinity. The antenna heights are relatively low and multipath scattering is assumed near BS as well as near MS. So, according to the Eccentro-Scattering model, BS and MS are located at the focal points of the Eccentro-Scattering disc as shown in Fig. 6.2(a). Good examples of this model are the shopping malls, street crossings and wireless Local Area Networks (WLANs).

In picocell and microcell environments, multipath signals arrive at BS antenna from all directions as shown in Fig. 6.2(a). Therefore, the azimuthal angular span, $\theta_{\text{span}}$, can always be considered as 360°.

The pdf of AoA of the multipaths at BS from all scattering points within the Eccentro-Scattering disc, $p_{\Theta}(\theta)$, in equation (3.10), can also be written as,

$$p_{\Theta}(\theta) = \frac{(1 - e^2)^{3/2}}{2\pi (1 - e \cos(\theta - \beta))^2}$$  \hspace{1cm} (6.11)

Considering the three motion scenarios and equation (6.2), change in eccentricity, $e$, of the Eccentro-Scattering disc can be written as,

$$e_{i+1} - e_i = \frac{d_{i+1} - d_i}{2a}$$  \hspace{1cm} (6.12)
Figure 6.3: Effect of MS motion on the pdf of AoA, various line styles show the plots at three different MS positions
6.3 Behavior of Spatial Characteristics under Mobile Motion

Figure 6.4: Behavior of $\theta_{\text{span}}$, $\bar{\theta}$ and $\sigma_{\theta}$ under the effect of MS motion in microcell and picocell environments

where $d_i$ and $d_{i+1}$ represent the MS-BS separations at positions $P_i$ and $P_{i+1}$, respectively, see Fig. 6.1 and 6.2(b).

Fig. 6.3(a), 6.3(b) and 6.3(c) show the effect of MS motion on the pdf of AoA of the multipaths at BS for microcell and picocell environments in MS motion scenarios 1, 2, and 3, respectively. The behavior of various spatial spread parameters under the effect of MS motion is also plotted in Fig. 6.4 and 6.5.

We see that,

- During motion scenario 1, the mean value of the pdf of AoA, $\bar{\theta}$, remains constant while a considerable change occurs in its SD, $\sigma_{\theta}$. As MS moves away from BS, SD decreases.
6.3 Behavior of Spatial Characteristics under Mobile Motion

![Figure 6.5: Behavior of $S_0$ and $\Lambda$ under the effect of MS motion in microcell and picocell environments](image)

and vice versa. Since, in microcell and picocell environments, multipath signals arrive at BS from all directions, angular span, $\theta_{\text{span}}$, remains $360^\circ$. Similar behavior of $\theta_{\text{span}}$ can also be seen in other scenarios.

In this scenario, since the arrival angles tend to cluster more and more tightly about $\bar{\theta}$ at each instant of time, $S_0$ and $\Lambda$ decrease sharply as shown in Fig. 6.5.

- During motion scenario 2, the mean value, $\bar{\theta}$, of the pdf of AoA changes at each instant of time while no change occurs in its SD, $\sigma_\theta$. Since shape of the pdf does not disturb, $S_0$ and $\Lambda$ remain constant.

- During motion scenario 3, both mean value, $\bar{\theta}$, of the pdf of AoA and SD, $\sigma_\theta$, change...
at each instant of time. Such varying effect can also be seen in $S_0$ and $\Lambda$. That is why this scenario is referred to as the general case and scenario 1 and scenario 2 are its special cases with $\phi_v = \beta$ and $\phi_v = \beta + \delta_\beta + \pi/2$, respectively.

### 6.3.2.2 Macrocell Environments

In macrocell environment, the BS is usually far away from MS, i.e. the distance between BS and MS is in the order of kilometers [14]. Rural, urban, suburban, and hilly areas are the best examples of macrocell environments. In macrocell environments, the multipath signals arriving at BS antenna result mainly from two-fold phenomena, viz.

1. Local scattering
2. Distant scattering

These phenomena have been explained in detail in chapter 1 and 3.

Fig. 6.6(a) shows the Eccentro-Scattering model for typical macrocell environment where MS is located at the center of the local scattering disc at distance $d$ from BS while the center of the dominant scattering disc is at distance $d_{BD}$ and $d_{MD}$ from BS and MS, respectively. $\theta_D$ is the angle between the line joining the center of the dominant scattering disc to BS and the $x$-axis whereas $\beta$ is the angle between LoS and $x$-axis.
6.3 Behavior of Spatial Characteristics under Mobile Motion

(a) Typical scattering model for macrocell environment

(b) Movement of scattering disc due to MS motion according to scenario 3

Figure 6.6: Macrocell environment
6.3 Behavior of Spatial Characteristics under Mobile Motion

The azimuthal angular spans due to local and distant scattering discs, $\theta_{L,\text{max}}$ and $\theta_{D,\text{max}}$, are defined in (3.18) and (3.19), respectively.

From the geometry of Fig. 6.6(a), the total azimuthal angular span, $\theta_{\text{span}}$, is defined as,

$$\theta_{\text{span}} = \theta_{L,\text{max}} + \theta_{D,\text{max}} + \theta_{D} - \beta$$  \hspace{1cm} (6.13)

The eccentricities of the local and distant Eccentro-Scattering discs, $e$ and $e_{D}$, do not depend on $d$ or $d_D$ but they instead depend on the terrain and clutter of the scattering regions and can be considered as fixed values between 0 and 1. For rural areas both are usually considered as 0s, i.e. circular scattering discs are assumed.

The pdf of AoA of the multipaths at BS defined in (3.27) can also be written as,

$$p_{\Theta}(\theta) = \begin{cases} 
2E(1-e^2)\cos(\theta - \beta)\sqrt{1-e^2\cos^2(\theta - \beta) - E^2\sin^2(\theta - \beta)} \\
\pi(1-e^2\cos^2(\theta - \beta))^2, & \beta - \theta_{L,\text{max}} \leq \theta \leq \beta + \theta_{L,\text{max}} \\
0, & \beta + \theta_{L,\text{max}} < \theta < \theta_{D} - \theta_{D,\text{max}} \\
2E_D(\cos(\theta - \theta_D) - e_{D}^2 \cos \theta \cos \theta_D)\sqrt{1-e_{D}^2 \cos^2 \theta - E_{D}^2 \sin^2(\theta - \theta_D)} \\
\pi(1-e_{D}^2 \cos^2 \theta)^2, & \theta_D - \theta_{D,\text{max}} \leq \theta \leq \theta_{D} + \theta_{D,\text{max}} \\
0, & \text{elsewhere} 
\end{cases}$$  \hspace{1cm} (6.14)

where $E = d/a$ and $E_D = d_{BD}/a_D$ are important ratios, which help in designing directional antennas for local and dominant distant scattering regions especially in rural areas.
Let MS moves from position $P_i$ to position $P_{i+1}$ traversing a small distance $\delta_d$ as given in (6.1); (also see Fig. 6.6(b)). The distance between BS and MS changes from $d_i$ to $d_{i+1}$ according to the general expression given in (6.2). Consequently, $E_i$ in (6.14) changes from $E_i$ to $E_{i+1}$ as,

$$E_{i+1}^2 = E_i^2 + 2\delta_d E_i \cos(\beta - \phi_v) + \delta_E^2$$  \hspace{1cm} (6.15)

where $\delta_E = \delta_d/a = v\delta t/a$. Since distant scattering clusters are usually the sets of stationary structures like hills and high-rise buildings in towns and villages, $d_{BD}$ remains constant during the course of MS motion. Therefore, change occurs only in local scattering parameters.

However, the dominant distant scattering disc has an immanent influence on the angular spread of the multipath signals at BS in macrocell environment. Therefore, the effect of
6.3 Behavior of Spatial Characteristics under Mobile Motion

mobile motion on the angular spread due to dominant distant scattering must be considered in addition to the aftermath of the motion scenarios given in section 6.2. We can classify the behavior of spatial characteristics of mobile channel under the combined effect of mobile motion and distant scattering disc into the following three situations.

**Situation 1:**

In this situation, the mobile moves towards (or away from) a dominant distant scattering cluster (like a town, a village or a hill) in the direction of line of sight (LoS) with BS. This situation usually develops during motion scenario 1 given in section 6.2. This situation is depicted in Fig. 6.8(a).

In this situation, \( d \) changes with respect to \( v \), but almost no change occurs in \( \beta \). On the other hand, angle spread, \( \sigma_\theta \), decreases (or increases) slightly but angular span, \( \theta_{\text{span}} \), and mean AoA, \( \bar{\theta} \), remain constant.

**Situation 2:**

In this situation, the mobile moves in a circular or quasi-circular path with respect to BS, and passes ahead or behind a dominant distant scattering cluster. This situation is usually developed during motion scenario 2 given in section 6.2. This situation is elaborated in Fig. 6.8(b).
Figure 6.8: Collective effect of distant scattering cluster and MS motion on the spatial spread of cellular mobile channel in macrocell environment
6.3 Behavior of Spatial Characteristics under Mobile Motion

Figure 6.9: Behavior of $S_0$ and $\Lambda$ under the effect of MS motion in macrocell environment

In this situation, $d$ does not change (or if it changes, the change is usually very minor), but major change occurs in the value of $\beta$, proportional to the distance travelled by MS. Thus in this situation, angle spread, $\sigma_{\theta}$, and angular span, $\theta_{\text{span}}$, first decrease as MS comes closer to the distant scattering cluster, stay fixed for some time proportional to the radius of cluster and then increase again. Mean AoA, $\bar{\theta}$, also changes continuously.

Situation 3:

In this situation, neither MS travels in the direction of LoS nor in a circular path with respect to BS. It follows the motion scenario 3 given in section 6.2 and passes alongside the
dominant distant scattering cluster. This situation is illustrated in Fig. 6.8(c).

In this situation, $d$ and $\beta$ both change at each instant of time in proportional to the velocity, $v$, of the MS. On the other hand, angle spread, $\sigma_\theta$, and angular span, $\theta_{\text{span}}$, both decrease as MS comes closer to the distant scattering cluster as seen from BS, but they increase when the distance between MS and distant scattering cluster increases. The effect of increasing or decreasing $d$ on $\sigma_\theta$ is mainly dependent on the closeness of the distant scattering cluster from the MS. Mean AoA, $\bar{\theta}$, also does not remain constant and alters with respect to the direction of motion of MS.

This situation is observed very often in rural and hilly areas. Thus the smart antenna system employed at BS must be designed accordingly in order to guarantee the reliability of service to the desired users.

The behavior of various spatial spread parameters for a moving mobile under the above situations is shown in Fig. 6.7 and 6.9. The effect of mobile motion on the pdf of AoA under these situations is also shown in Fig. 6.3(d), 6.3(e) and 6.3(f).

Behavior of angle spread in rural areas, plotted in Fig. 3.2.5 of COST 259 [14] can easily be explained on the basis of above-mentioned situations. This behavior strictly depends on the angle of MS motion, $\phi_v$, and the location of distant scattering cluster. Therefore, it is always inconsistent with the increase or decrease in MS-BS separation.
6.4 Behavior of Temporal Characteristics under Mobile Motion

6.4.1 Temporal Channel Model

Based on the assumptions given in section 2.2 of chapter 2, an nth bounding ellipse defines a specific set of scatterers that give rise to multipath components arriving between time delays $\tau_n$ and $\tau_{n+1} = \tau_n + \delta_r$. A temporal model along with all employed parameters has been explained in detail in section 5.2 of chapter 5, (also see Fig 5.1).

Let a specific time delay $\tau_n$ define a set of scatterers bounded by nth bounding ellipse. Then the semi-major axis $a_{\tau_n}$ and semi-minor axis $b_{\tau_n}$ of the nth bounding ellipse can be written as,

\[
a_{\tau_n} = \frac{c\tau_n}{2} \quad (6.16)
\]

\[
b_{\tau_n} = \frac{1}{2} \sqrt{4a_{\tau_n}^2 - d^2} \quad (6.17)
\]

As we mentioned earlier in chapter 5, we denote the semi-major axis and eccentricity of the outermost bounding ellipse by the notations $a_{\tau_{\text{max}}}$ and $e_{\tau_{\text{max}}}$, respectively. Both variables are related to the maximum delay spread, $\tau_{\text{max}}$. Use of $a_{\tau_n}$ should not be confused with the notation $a$ in section 6.3, where $a$ denotes the semi-major axis of a fixed Eccentro-Scattering disc in a spatial channel model. However, $a_{\tau_{\text{max}}}$ and $e_{\tau_{\text{max}}}$ are equivalent to $a$ and $e$ of the Eccentro-Scattering spatial channel model in the case of picocell and microcell environments,
6.4 Behavior of Temporal Characteristics under Mobile Motion

![Diagram of power delay profile](image_url)

Figure 6.10: A general power delay profile

but not equivalent to \( a \) and \( e \) of the Eccentro-Scattering spatial channel model in macrocell environment. This is due to the fact that \( a \) and \( e \) of the Eccentro-Scattering disc in case of picocell and microcell environments depend on \( \tau_{\text{max}} \), while being independent of \( \tau_{\text{max}} \) in macrocell environment, they depend only on the terrain and orientation of the streets, roads or valleys.
6.4 Behavior of Temporal Characteristics under Mobile Motion

6.4.2 Some Important Temporal Parameters

**Delay in LoS, \( \tau_0 \):** This is the time at which signal travels between BS and MS in LoS, whether LoS exists or not. That is,

\[
\tau_0 = \frac{d}{c}
\]

(6.18)

**Mean Excess Delay, \( \bar{\tau} \):** This is the first moment of the power-delay profile, \( P(\tau) \), with respect to delay in LoS, \( \tau_0 \). That is [80],

\[
\bar{\tau} = \int (\tau_n - \tau_0)P(\tau_n)d\tau_n
\]

(6.19)

**Maximum Delay, \( \tau_{\text{max}} \):** This can be specified as the time delay for which the power of the multipath component, \( P(\tau_n) \), falls below a specific power level, referred to as the threshold value. When the signal level is lower than the threshold, it is passed as noise [24].

**Maximum Excess Delay, \( \tau_e \):** This is the time difference between the maximum delay, \( \tau_{\text{max}} \), and the delay in LoS, \( \tau_0 \), [24]. That is,

\[
\tau_e = \tau_{\text{max}} - \tau_0
\]

(6.20)

**rms Delay Spread, \( \sigma_\tau \):** This is the square root of the second central moment of the power-delay profile, \( P(\tau_n) \). This can also be referred to as the standard deviation of \( P(\tau_n) \) about the mean excess delay, \( \bar{\tau} \). That is, [8]

\[
\sigma_\tau = \sqrt{\int (\tau_n - \tau_0 - \bar{\tau})^2P(\tau_n)d\tau_n}
\]

(6.21)
6.4 Behavior of Temporal Characteristics under Mobile Motion

The effect of temporal dispersion on the performance of a digital receiver can be reliably related to the rms delay spread, independently of the shape of power-delay profile [80].

These time-delay spread parameters are illustrated in Fig. 6.10.

6.4.3 Lifetime of Scatterers

As MS travels, the scattering environment changes such that some scatterers move out of the scattering disc and some others move in; as a result new multipath components contribute to the received signal. This phenomenon is referred to as multipath generation [81]. The
distance between BS and MS, $d$, and maximum delay, $\tau_{\text{max}}$, collectively form a bounding ellipse with parameters $e_{\tau_{\text{max}}}$ and $a_{\tau_{\text{max}}}$ as given in (5.3) and (6.16). This bounding ellipse defines the outer boundary of the scattering points associated with time delays up to $\tau_{\text{max}}$. Thus, MS motion gives rise to the phenomenon of multipath generation as well as to an alteration in the shape of the bounding ellipse.

According to terrain and clutter of the surroundings, MS motion affects the bounding ellipse in one of the following two cases:

6.4.3.1 Case 1

This case defines a situation where $\tau_{\text{max}}$ is kept fixed during the course of MS motion, see Fig. 6.11(a). Namely, as MS moves it loses some scatterers but does not attain new influential ones that can affect the temporal spread of the received signal. In other words, it can be said that the lifetime of multipath components has finished for the present cell and MS should be handed over, immediately, to a new BS in order to guarantee continuous reception. In such a case, $\tau_{\text{max}}$ and consequently $a_{\tau_{\text{max}}}$ do not change for the current cell while $e_{\tau_{\text{max}}}$ and $b_{\tau_{\text{max}}}$ change due to change in $d$. Also, $\tau_0$ and $\sigma_\tau$ incur a change in their values. Considering three motion scenarios and (6.2), change in $e_{\tau_{\text{max}}}$ can be written as,

$$e_{\tau_{\text{max}}, i+1} - e_{\tau_{\text{max}}, i} = \frac{d_{i+1} - d_i}{c\,\tau_{\text{max}}}$$

(6.22)

In this case, eccentricity of the outer bounding ellipse, $e_{\tau_{\text{max}}}$, takes a value in the range
6.4 Behavior of Temporal Characteristics under Mobile Motion

Figure 6.12: Behavior of power delay profile under the effect of MS motion
between 0 and 1 during the course of MS motion. Hence, this value increases as the distance between BS and MS increases such that $e_{\tau_{\text{max}}}$ approaches 1 at the edge of the cell where the signal power falls lower than the threshold value. Before $e_{\tau_{\text{max}}}$ approaches 1, MS should be handed over to the new cell and it comes under the influence of the new cell’s BS. Therefore, in this case handover depends either on the power threshold or on the situation that $\tau_0$ approaches $\tau_{\text{max}}$ (i.e. $e_{\tau_{\text{max}}}$ approaches 1 due to the terrain and clutter of the surroundings). Effect of MS motion on the pdf of ToA and other statistical parameters has been illustrated in Fig. 6.12(a) for this case.

### 6.4.3.2 Case 2

This case defines a situation where $\sigma_\tau$ or $\tau_e$ is kept fixed during the course of MS motion as long as MS remains in the same cell. In this situation, both $\tau_0$ and $\tau_{\text{max}}$ change according to the change in $d$, but the eccentricity of the outer bounding ellipse, $e_{\tau_{\text{max}}}$, does not incur change in its value. Instead, the semi-major axis of the outer bounding ellipse, $a_{\tau_{\text{max}}}$, which is a measure of $\tau_{\text{max}}$, changes as shown in Fig. 6.11(b). Considering equation (6.2) and the three motion scenarios, change in $a_{\tau_{\text{max}}}$ can be written as,

$$a_{\tau_{\text{max}}}, i+1 - a_{\tau_{\text{max}}}, i = \frac{d_{i+1} - d_i}{2 e_{\tau_{\text{max}}}}$$  

(6.23)

In this case, MS attains more and more scatterers from the surroundings, in addition to the existing ones at each instant of time. Here, $a_{\tau_{\text{max}}}$ gets a change in its value between $R_0$ and $\frac{c\tau_{\text{ex}}}{2}$; where, $\tau_{\text{ex}}$ is the extreme maximum delay at which the signal power drops below the
6.4 Behavior of Temporal Characteristics under Mobile Motion

Figure 6.13: Movement of scattering discs due to MS motion in (a) picocells and microcells (b) macrocells

threshold value and MS is then handed over to a new BS; and, $R_0$ is an arbitrary constant value depending on the close-in-reference distance which is the minimum practical separation between BS and MS. Effect of MS motion on the pdf of ToA and other statistical parameters has been illustrated in Fig. 6.12(b) for this case.
6.4 Behavior of Temporal Characteristics under Mobile Motion

Figure 6.14: Behavior of $\sigma_\tau$, $\tau_e$, $\tau_0$, $\bar{\tau}$ and $\tau_{\text{max}}$ in picocells and microcells under the effect of MS motion when lifetime of scatterers is based on case 1 and case 2

6.4.4 Effect of Mobile Motion on ToA Statistics

6.4.4.1 Picocell and Microcell Environments

In picocell and microcell environments, the Eccentro-Scattering disc covers the whole area bounded by the outer bounding ellipse, as shown in Fig. 6.13(a). The pdf of ToA of the multipaths at BS from all scattering points within the outer bounding ellipse or Eccentro-Scattering disc of picocell/microcell environments, $p(\tau_n)$, in (5.16) can be re-written as,

$$p(\tau_n) = \frac{c(2c^2\tau^2_n - d^2)}{4a_{\text{max}}^2 \sqrt{1 - c^2_{\text{max}} \sqrt{c^2\tau^2_n - d^2}}}$$  \hspace{1cm} (6.24)
6.4 Behavior of Temporal Characteristics under Mobile Motion

Figure 6.15: Effect of MS motion on the pdf of ToA; various line styles show the plots at different MS positions

Here, the effect of motion on the temporal statistics of the channel can be explained on the basis of the lifetime of scatterers discussed earlier.

**Case 1:** In this case, as mentioned earlier, $\tau_{\text{max}}$ is kept fixed during the course of MS motion while the eccentricity of the outer bounding ellipse, $e_{\tau_{\text{max}}}$, changes due to the change in $d$ according to (6.2) and (6.22). Therefore, the semi-major axis of the outer bounding ellipse, $a_{\tau_{\text{max}}}$, remains constant. Since $\tau_{\text{max}}$ is kept fixed, so with changing $d$, the values of $\tau_0$, $\tau_e$, and $\sigma_{\tau}$ change. Fig. 6.15(a) represents the plots of the pdf of ToA at various MS positions.
6.4 Behavior of Temporal Characteristics under Mobile Motion

**Case 2:** In this case, as mentioned earlier, $\sigma_\tau$, or $\tau_e$ is kept fixed during the course of MS motion while both $\tau_0$ and $\tau_{\text{max}}$ change. Therefore, the eccentricity of the outer bounding ellipse, $e_{\tau_{\text{max}}}$, also remains constant and a change occurs in $a_{\tau_{\text{max}}}$ according to (6.23), due to the change in $d$ according to (6.2). In other words, the shape of the pdf of ToA does not alter as a result of MS motion. Fig. 6.15(b) represents the plots of the pdf of ToA at various MS positions for this case.

Fig. 6.14 shows the behavior of various temporal spread parameters under the effect of motion in picocell and microcell environments.

6.4.4.2 Macrocell Environments

In macrocell environments, the outer bounding ellipse intersects some part of the scattering disc around MS as shown in Fig. 6.13(b). As MS moves from position $P_i$ to position $P_{i+1}$, it re-acquires almost the same scattering environment at the new position without having any change in its shape. However, since change occurs in MS-BS separation, $d$, temporal spread parameters are significantly affected. Let $R$ be the effective radius of the scattering disc around MS and $e_{\tau_{\text{max}}}$ be the eccentricity of the outer bounding ellipse. The pdf of ToA of the multipaths at BS from all scattering points within the outer bounding ellipse, $p(\tau_n)$, in (5.31) for macrocell environment can also be written as,

$$p_\tau(\tau_n) = \frac{c(2r^2 - e_{\tau_{\text{max}}}^2)}{\pi m R \sqrt{r^2 - e_{\tau_{\text{max}}}^2}} \left[ \frac{\pi}{2} - \tan^{-1} \left( \frac{\sqrt{e_{\tau_{\text{max}}}^2 + (r - m)}}{e_{\tau_{\text{max}}}^2 - (r - m)} \right) - \frac{(r - m) \sqrt{e_{\tau_{\text{max}}}^2 - (r - m)^2}}{2(2r^2 - e_{\tau_{\text{max}}}^2)} \right]$$

(6.25)
6.4 Behavior of Temporal Characteristics under Mobile Motion

Figure 6.16: Behavior of $\sigma_\tau$, $\tau_e$, $\tau_0$, $\bar{\tau}$ and $\tau_{\text{max}}$ in macrocells under the effect of MS motion when lifetime of scatterers is based on case 1 and case 2

where $r = \tau_n/\tau_{\text{max}}$ and $m = R/a_{\tau_{\text{max}}}$. 

The effect of change in MS-BS separation on temporal spread parameters in macrocell environment can also be discussed on the basis of the lifetime of scatterers. In case 1, $\tau_{\text{max}}$ is kept fixed during the course of MS motion while the eccentricity of the outer bounding ellipse, $e_{\tau_{\text{max}}}$, changes due to the change in $d$. Likewise, the values of $\tau_0$, $\tau_e$, and $\sigma_\tau$ also change as shown in Fig. 6.16. Also, Fig. 6.15(c) represents the plots of the pdf of ToA at various MS positions.

On the other hand, in case 2, $\sigma_\tau$, or $\tau_e$ is kept fixed during the course of MS motion while both $\tau_0$ and $\tau_{\text{max}}$ are allowed to change. Thus, the shape of the pdf of ToA does not
alter as a result of MS motion. Fig. 6.15(d) represents the plots of the pdf of ToA at various MS positions for case 2. Fig. 6.16 shows the behavior of various temporal spread parameters under the effect of motion in macrocell environments.

Comparing Fig. 6.14 and Fig. 6.16, we observe that the values of $\tau_e$ and $\sigma_{\tau}$ in macrocell environments are very small as compared to those of $\tau_0$ and $\tau_{max}$. This is because of large BS-MS separations and concentrations of scatterers in the vicinity of MS. It means that the approach of keeping $\sigma_{\tau}$ or $\tau_e$ fixed (i.e. case 2) is the most appropriate for macrocells. Otherwise, temporal array processing receivers like Rake receivers cannot offer outstanding performance. On the other hand, in picocell and microcell environments, both approaches (case 1 and case 2) are equally applicable and either of them can be used, according to the scattering situation (terrain) in the vicinity of BS and MS.

6.5 Conclusion

In time-varying fading channels, a direct representation of the distribution of AoA, being a prerequisite in calculating correlation coefficients, is needed to assess the potential of beam-oriented algorithms such as Space Division Multiple Access (SDMA) [23, 82]. On the other hand, besides the handy use of the delay spread in determining the coherence bandwidth of a particular system [22], it is the main cause of frequency selective fading. It has also attracted the attention of many researchers in order to design efficient receivers in wireless
mobile communications. Since mobile motion is responsible for the time variability of cellular mobile channel, it is necessary to investigate its effect on the spatial and temporal statistics of the cellular mobile channel. In this chapter, we have discussed several motion scenarios that are responsible for such an effect.

We have formulated the changes in the AoA and ToA distributions of the multipath signals at BS during the course of MS motion for different cellular environments. We have plotted the behavior of all important spatial and temporal statistical parameters under the effect of mobile motion. The proposed theoretical results in spatial characteristics can be extended to characterizing and tracking transient behavior of Doppler spread in time-varying fast fading channel; likewise the proposed theoretical results in temporal characteristics can be utilized in designing efficient equalizers for combating inter-symbol interference (ISI) in time-varying frequency-selective fading channels.
Chapter 7

Fast Fading Channel Modeling for Single-Carrier DS-CDMA Systems

In this chapter, section 7.1 presents a comprehensive overview of adaptive multiuser detection in single-carrier DS-CDMA system. In section 7.2, a state-space model is developed on the basis of the statistics of time-varying multipath fading channel. Section 7.3 presents the Kalman filter based adaptive detection scheme for DS-CDMA system, which utilizes an autoregressive (AR) model for signature sequence estimation. Section 7.4 summarizes the chapter and presents concluding remarks.
7.1 Overview

7.1.1 History of DS-CDMA Detectors

In a code division multiple access spread spectrum (CDMA) system a number of users simultaneously transmit information over a common channel using different code sequences referred to as signatures. The receiver usually knows the assigned signatures and correlates them with the received signal. If the assigned signatures are orthogonal, then a bank of decoupled single-user detectors consisting of matched filters followed by threshold detectors can achieve optimum demodulation [83, 84].

In most of the CDMA systems of practical importance, transmitters send information independently. Therefore, signals from different users arrive asynchronously at the receiver. Since their relative time delays are arbitrary, the cross-correlation between the received signals coming from different users is non-zero. To achieve a low level of interference the assigned signatures need to have low cross-correlations for all relative time delays. A low cross-correlation between signatures is obtained by designing a set of mutually orthogonal signatures [83]. In practice, however, it is difficult to keep the signatures orthogonal in synchronous systems due to many impairments of the channel.

The presence of multiple access interference (MAI) has been considered as the major limiting factor in CDMA systems. Many techniques have been proposed to decode users successfully in the presence of MAI [84–90], while addressing CDMA demodulation problem.
7.1 Overview

The matched filter (MF) receiver demodulates the received signal with the use of a single-user detector which consists of a matched filter followed by a threshold detector [84]. In MF receivers, the MAI is modeled as additive white Gaussian noise (AWGN), ignoring its cyclo-stationary character [84] (especially in case of short-code CDMA). An alternative receiver structure is a maximum likelihood multiuser receiver (MLMR) for synchronous and asynchronous transmission. The MLMR consists of a bank of matched filters followed by a Viterbi maximum likelihood detector [91]. The computational complexity of this optimum demodulator increases exponentially with the number of users [92].

The concept of interference suppression by exploiting its cyclo-stationary nature has been used elsewhere, notably in [93], with applications to digital subscriber lines. MAI cancellation has been used properly in systems where MAI is demodulated and subtracted from the received signal prior to the user of interest signal detection. This method of MAI detection and cancellation is combined with an adaptive antenna array in [94]. The concept is critically dependent on successful MAI demodulation [85]. A significant improvement in exploiting the cyclo-stationary nature of MAI which led to signature sequence adaptation is obtained in a number of adaptive receiver structures which are very effective in MAI cancellation and are moderately complex [85]. An adaptive filter is necessary to handle time varying system parameters. But it is shown that the adaptive linear receiver is able to completely remove the effect of multipath propagation provided the multipath parameter variations are slower than the adaptive algorithm convergence speed.
7.1 Overview

A general approach to the design of multiuser systems is based on receiver optimization. Due to the exponential complexity of MLMR, suboptimum multiuser detection has been an active area of research. As an alternative to receiver optimization for synchronous multiuser channels, transmitter precoding has been recently proposed [86, 95–97]. So considering the good behavior of linear adaptive receiver in MAI cancellation, an improvement was made in the same technique by shifting the bulk of processing to the transmitter and making it jointly adaptive with the receiver [86]. With this joint adaptation of transmitter and receiver, better MAI suppression is achieved and consequently a larger number of independent users were accommodated per unit of bandwidth relative to the systems with adaptive receivers only.

The concept of the joint adaptive transmitter-receiver is based on feedback information from the corresponding receiver. The information obtained from the receiver is used to calculate the optimum signature for the respective transmitter. The signatures are adaptively adjusted according to the MSE criterion of optimality during the training period as well as during the data transmission [86].

The joint transmitter-receiver optimization as well as transmitter precoding relies on channel knowledge. When the system operates in the time-duplex mode, the channels’ responses can be estimated at the base station. Otherwise, channel estimates obtained by mobile receivers have to be transmitted to the base via feedback channels. It is sufficient to transmit channel estimates once per packet. The crucial assumptions for this scheme to work are that channel characteristics remain constant over the block of precoded bits and the transmitter has knowledge (at least sufficiently accurate) about all multipath profiles.
7.1 Overview

Selection of an ensemble of signature sequences that minimize total interference power with matched filter (MF) receivers is considered in [98, 99].

Transmitter precoding assumes that the symbols of the users on the downlink are already modulated with some linearly independent signature sequences, and essentially undoes the cross correlation introduced by the non-orthogonality of these signature sequences. A drawback associated with transmitter adaptation in general is the feedback bandwidth required, which increases with the number of transmitter coefficients to be estimated [90]. It means that the feedback transmission of filter coefficients to the transmitter must not require excessive bandwidth. These concerns need to be addressed for signature optimization to be useful in practical systems. An improvement to tackle this problem is presented in [90]. A ‘reduced-rank’ transmitter adaptation scheme, in which each signature sequence is constrained to lie in a lower dimensional subspace, spanned by some orthogonal basis, is presented in [90]. The weights for the basis are then selected to optimize the performance criterion, the output signal-to-interference-plus noise ratio (SINR). Different orthogonal bases are assigned to different users. Selection of the subspace dimension allows a tradeoff between the number of parameters to be estimated and steady-state performance. Their results show that adaptive receivers based on a least squares performance criterion generally perform worse than the non-adaptive RAKE, or MF receiver, since the adaptive receiver introduces tracking error when the signatures are time-varying [90].

As far as the type of signature waveform or ‘code’ is concerned, it also affects the design
and performance of DS-CDMA detector. There are two types of codes commonly used in DS-CDMA. They are:

1. Short or Repeated code

2. Long or Non-repeated code

The use of short code in DS-CDMA systems gives rise to cyclo-stationary MAI which can be exploited in adaptive detection as discussed earlier; whereas long code is usually difficult to estimate with gradient-based algorithms over time-varying channels. However, MAI in the case of long code, is usually assumed as Gaussian, which simplifies the receiver structure.

The use of short or repeated signature sequences in DS-CDMA is shown to be of great advantage for avoiding interference in adaptive techniques for multiuser detection [85, 86, 90]. The receiver structure in [85] uses short codes and requires no knowledge of the transmitted signature sequences. Instead, it requires training bits and symbol timing of the desired user. The minimization of the external information requirement, whether in form of training sequence or knowledge of signature waveforms, has been a hot area of research in recent years. In the adaptive operations, some external information, (sometimes in the form of training sequences) must be sent not only during the startup period but also after sudden changes in the channel response, or when a new active user appears [88, 89]. Especially in highly time-varying channels or fast fading environment the need to retransmit training sequence is very necessary otherwise performance of the multiuser detector degrades significantly. This
additional burden exploits a large part of the bandwidth resources with no beneficial use. Thus a large effort has been made in eliminating the need for training sequences by proposing blind adaptive multiuser detection [88, 89, 100].

### 7.1.2 Time-Varying Nature of the DS-CDMA Channel

The classical approaches [85, 89] used so far for signature adaptation suppose that either multipath multiuser channels are fixed (whether known or unknown) or are slowly time-varying. But in real life mobile channels are highly time-varying and their time-varying nature can be interpreted as a dynamic system with uncertainties in its coefficients [35]. As we know the mobile communication channel introduces a variety of transmission impairments including multipath fading, noise and interference. Many of the signal processing algorithms used to mitigate the multipath and fading aspects of the mobile channel require accurate knowledge or estimates of the channel state [87].

In DS-CDMA systems, accurate detection of transmitted symbols depends mainly on the accurate estimation of received code waveforms. The performance of adaptive multiuser detector degrades significantly if signature estimates are not accurate. This lack of accuracy can be due to high level of interference caused by non-ideal cross-correlation properties of time-varying signatures of different users. At high vehicle speeds (> 100 Km/h), the channel conditions change significantly. So the signatures of different users in the system get highly correlated and the performance of the system degrades. To combat this dynamic nature of
7.1 Overview

time-varying channels and other fading effects, state-space approach has been proposed as a good technique [34, 101].

7.1.3 Contributions of the Chapter

Autoregressive (AR) model is usually considered the simplest way to capture the dynamic nature of time-varying flat fading channel [102–107]. We thus develop an AR model of time-varying flat fading channel by using its second order fading statistics and utilize it further to establish a linear state-space equation pair for signature sequence estimation in direct sequence code division multiple access (DS-CDMA) system. We then exploit the Kalman filtering approach to incorporate our proposed state-space equation pair in an algorithm, meant for estimating channel-distorted received signature sequences. It is an established fact [34] that the Kalman filter is a good optimal linear minimum mean squared error (MMSE) detector if a first order linear state-space model is applied to DS-CDMA system. As mentioned earlier, we also use the Kalman filter as the MMSE solution for signature distortions caused by the time-varying fading channel. However, different from the model used in [34], where the unknown transmitted symbol vector has been used as state-vector, we use channel-distorted received signature vector as the state-vector in our model. This approach is based on the fact that the time-varying channel behaves as the AR model depending on its past values [23, 35]. In our proposed receiver structure, the need for training sequence is bound to the startup period only. Later on, the receiver adapts itself to the changes of the channel during data
transmission depending on previous decisions. Simulation results show that being based on
the Kalman filter and of non-gradient nature, our proposed algorithm combats effectively
the impairments and fading effects caused by time-varying multipath channel.

7.2 State-Space Approach in Multipath Fading Channel Modeling

The performance of a wireless communication system strictly depends on the extent of the
prior knowledge of the time-varying fading channels [20], which in turn depends on the fading
statistics utilized in the channel estimator. There is a lot of work on designing optimum
and sub-optimum channel estimators like the Kalman trackers [106, 107] or Wiener Least
Mean Square (WLMS) predictors [108], that utilize the fading statistics of cellular mobile
channel. State-space model is the best way to develop a channel estimator based on the valid
assumption that time-varying fading channel is Markovian in nature. Therefore, the varying part
of the channel is modeled either Autoregressive (AR) [102, 104], or Autoregressive Moving-Average
(ARMA) [109], based on Jakes-Reudink autocorrelation function [23]. There is also a need for a highly time-selective fast fading channel model, which can become a basis for optimum channel estimators for highly spatio-resolution systems like multi-input multi-output (MIMO) and space division multiplexing (SDMA) systems. Our motivation to present this section is thus to develop a state-space model based on the statistics of
7.2 State-Space Approach in Multipath Fading Channel Modeling

time-varying fast fading channels, for both the dynamic Rayleigh and Ricean processes.

7.2.1 Characterization of Multipath Fading Channels

Consider the equivalent low-pass signal received over a time-variant fading multipath channel [67]

\[ r(t) = \sum_l \alpha_l(t) e^{-2j\pi f_c \tau_l(t)} s(t - \tau_l(t)) + n(t) \]  

(7.1)

where \( s(t) \) is the equivalent low-pass transmitted signal, \( f_c \) is the carrier frequency, \( \alpha_l \) is the attenuation factor for the signal received on \( l \)th path, \( \tau_l(t) \) is the propagation delay for the \( l \)th path and \( n(t) \) is the additive white Gaussian noise with zero mean and \( \sigma_n^2 \) variance.

Therefore, time-variant impulse response \( h(\tau; t) \) of the fading multipath channel comprised of \( L + 1 \) paths can be written as,

\[ h(\tau; t) = \sum_{l=0}^{L} \alpha_l(t)e^{-2j\pi f_c \tau_l(t)}\delta(\tau - \tau_l(t)) \]  

(7.2)

\( h(\tau; t) \) is a complex-valued Gaussian random process in the \( t \) variable, and the amplitude variations in the received signal (7.1) are due to the time-variant multipath characteristics of \( h(\tau; t) \). When the impulse response \( h(\tau; t) \) is modeled as a zero-mean complex-valued Gaussian process, the envelope \(|h(\tau; t)|\) at any instant \( t \) is Rayleigh-distributed. In the event that there are fixed scatterers or signal reflectors in the medium, in addition to randomly moving scatterers, \(|h(\tau; t)|\) has a Rice distribution [67]. Furthermore, if the differential path delays \( \tau_i - \tau_j \) are small compared to the duration of a modulated symbol; then the received signal can be considered to exhibit flat-fading and channel can be written as independent of
Writing the channel $h(\tau; t)$ as the combination of fixed and time-varying parts [110], we get,

$$h(t) = \sqrt{\frac{K_t}{K_t + 1}} \alpha_0(t)e^{-2j\pi f_c \tau_0(t)} + \frac{1}{\sqrt{K_t + 1}} \lim_{M \to \infty} \sum_{l=1}^{L} \alpha_l(t)e^{-2j\pi f_c \tau_l(t)}$$

where,

- $h_c(t)$ and $h_d(t)$ are the line of sight (LoS) and diffuse components of the time-varying channel $h(t)$.

- $K_t = E\{|h_c(t)|^2/|h_d(t)|^2\}$ is the ratio of the LoS component’s power to that of the diffuse component and is known as the Ricean factor [110].

- $f_D$ is the maximum Doppler spread of the channel and can be defined as $f_D = v/\lambda$, where $v$ is the velocity of the mobile, and $\lambda$ is the wavelength of the signal.

- $\psi_i, i = 1, ..., L$ is the angle between the $i$th incoming multipath signal and the mobile direction; the subscript $i = 0$ denotes the LoS component.

- $\varphi_i, i = 1, ..., L$ is the phase angle due to the $i$th incoming multipath signal and is equal to $-2\pi f_c \tau_i(t)$. In the absence of LoS component, i.e. in a Rayleigh channel, the phases $\varphi_i$ are uniformly distributed on $[-\pi, \pi]$.

$L$ in Equation (7.3) can be made arbitrarily large enough to ensure $h_d(t)$ to be a complex-valued Gaussian process as discussed earlier. According to Bello’s WSSUS model [107, 111],
all the channel multipaths are independent; therefore, each term $h_t^{(i)}, i = 1, ..., L$, in the summation of time-varying part $h_t$ in (7.3) is a zero-mean, wide-sense-stationary complex Gaussian process, uncorrelated with any other term $h_t^{(l\neq i)}$. So the autocorrelation function $R(\Delta t)$ of the channel $h$ for the time-lag $\Delta t$ can be written as,

$$R(\Delta t) = E\{h(t)h^*(t + \Delta t)\}$$  \hspace{1cm} (7.4)

where $E\{\cdot\}$ represents the expectation and $x^*$ is the complex conjugate of a complex-valued variable $x$.

Using (7.3), we get [110]

$$R(\Delta t) = \frac{K_t}{K_t + 1} e^{-j2\pi f_D \cos(\psi_0)\Delta t} + \frac{1}{K_t + 1} \int_{-\pi}^{\pi} p(\psi)e^{-j2\pi f_D \cos(\psi)\Delta t} d\psi$$  \hspace{1cm} (7.5)

where $p(\psi)$ is the distribution of angle of arrival of incoming multipaths with respect to the direction of MS motion, $\phi_v$, as shown in Fig. 7.1. It is evident from Equation (7.5) that $R(\Delta t)$ depends on $p(\psi)$. Let $\phi$ be the angle of arrival (AoA) of the multipath signal at MS.
with respect to the $x$-axis as shown in Fig. 7.1. Then the distribution of the angle of arrival at MS, $p(\phi)$, can be defined for various cellular environments as follows:

**Picocell and Microcell Environments:** As discussed in chapter 2, the Eccentro-Scattering model for picocell and microcell environments consists of an elliptical scattering disc with BS and MS on its foci, as shown in Fig. 7.2. In these environments, scatterers are usually uniformly distributed. Due to the symmetry of the focal points of the ellipse with respect to its center, the distribution of AoA at MS will be the same as that at BS given in (3.9). Therefore,

$$p_\Phi(\phi) = \frac{(4a^2 - d^2)^{3/2}}{4\pi a (2a - d \cos \phi)^2}$$  \hspace{1cm} (7.6)

where $a$ is the semi-major axis of the pico/microcell Eccentro-Scattering disc and $d$ is the MS-BS separation. In these environments, the LoS component or specular component, $h_c(t)$, usually exists.

**Macrocell Environments** In macrocell environments, the MS is usually surrounded by
uniformly or Gaussian distributed scatterers in an Eccentro-Scattering disc as shown in Fig. 7.3. The BS in macrocells is usually free from local scatterers [13]. Considering the geometry of the scattering disc, the distribution of AoA at MS is given as,

\[ p_\phi(\phi) = \frac{ab}{2\pi(a^2 \sin^2 \phi + b^2 \cos^2 \phi)} \] (7.7)

where \( a \) and \( b \) are the semi-major and semi-minor axes of the macrocell Eccentro-Scattering disc. In flat-rural macrocell areas, the Eccentro-Scattering disc becomes circular or quasi-circular and the distribution of AoA at MS becomes uniform. Hence,

\[ p_\phi(\phi) = \frac{1}{2\pi} \] (7.8)

Since in picocell and microcell environments the velocity of MS is very low, there is no considerable Doppler effect on the carrier frequency. Hence, channel can be considered as time-invariant for the duration of at least one data frame. Therefore, there is no need of high-complexity channel estimation algorithms, which are usually meant for rapidly time-varying channels. An ordinary channel estimator utilizing low-complexity LMS algorithm
7.2 State-Space Approach in Multipath Fading Channel Modeling

can be employed at either of two wireless link ends. The main goal of our research work in this section is to model a fast fading channel estimator that combats the rapid variations of the channel. Thus, we will put emphasis on the macrocellular case where the velocity of MS is usually very high (i.e., > 120 km/h).

In macrocellular environments, the LoS component, $h_c(t)$, of the channel usually does not exist and the channel behaves completely as ‘Rayleigh’ fading process [13]; therefore, $K_t = 0$. Using (7.8), we can also write for $p(\psi)$,

$$p_\psi(\psi) = \frac{1}{2\pi} \quad (7.9)$$

Therefore, $R(\Delta t)$ in (7.5) can be finally written as,

$$R(\Delta t) = \sigma_h^2 J_0(2\pi f_D \Delta t) \quad (7.10)$$

where $J_0(\cdot)$ is the zeroth order Bessel function of the first kind and $\sigma_h^2 = R(0)$ is the variance of time-varying fading channel. Similar result for the autocorrelation function was first reported in [23] and thus is known as ‘Jakes’ Model. Without loss of generality, we can assume $\sigma_h^2 = 1$ in order to simplify our results.

To simulate the structured variations of time-selective wireless fading channel, three types of linear models are usually considered [103, 104, 109, 112, 113], which are:

1. Autoregressive (AR) or ‘All-pole’ model

2. Moving average (MA) or ‘All-zero’ model

187
3. Autoregressive moving average (ARMA) model

Out of these three, the AR model is the most frequently used model because of its simplicity and ease of designing (i.e., the equations that determine its parameters are linear). The Yule-Walker equations [112, 113], which are used to determine the parameters of the model, become the normal equations in case of the AR model. The Levinson-Durbin recurrent algorithm is used to solve these equations. The key of the algorithm is the recursive computation of the filter coefficients, beginning with the first order and increasing the order recursively, using the lower order solutions to obtain the solution to the next higher order [103, 112].

Selecting the order is another difficult problem in developing a linear model. In [114], the information theoretic results show that the first-order AR model provides a sufficiently accurate model for time-selective fading channels and, therefore, we will adopt it henceforth. Thus, using discrete-time notations, \( h(i) \) varies according to [35]

\[
h(i) = \xi h(i - 1) + v(i) \tag{7.11}
\]

where \( \xi \) is the autoregressive (AR) coefficient which accounts for the variations in the channel due to Doppler shift, and \( v(i) \) is the zero-mean complex Gaussian noise with covariance \( \sigma_v^2 \) and is statistically independent of \( h(i - 1) \).

Using Yule-Walker equations [35, 112, 113], \( \xi \) and \( \sigma_v^2 \) can be written as,

\[
\xi = R(\Delta t) = J_0(2\pi f_D \Delta t) \tag{7.12}
\]

\[
\sigma_v^2 = 1 - |\xi|^2 \tag{7.13}
\]
7.2.2 State-Space Model of the Communication System over Fast Fading Multipath Channels

If we consider $N_t$ tap channel, then we can rewrite equations (7.1) and (7.11) in vector form as,

$$\begin{align*}
\mathbf{h}(i) &= \Xi \mathbf{h}(i-1) + \mathbf{v}(i) \\
\mathbf{r}(i) &= \mathbf{s}^T(i)\mathbf{h}(i) + n(i)
\end{align*}$$

(7.14)

where, $\Xi = \text{diag}\{\xi_0, \xi_1, \cdots, \xi_{N_t-2}, \xi_{N_t-1}\}$, $\mathbf{h}(i) = [h_0(i) \ h_1(i) \ \cdots \ h_{N_t-2} \ h_{N_t-1}]^T$, $\mathbf{v}(i) = [v_0(i) \ v_1(i) \ \cdots \ v_{N_t-2} \ v_{N_t-1}]^T$ and $\mathbf{s}(i) = [s_0(i) \ s_1(i) \ \cdots \ s_{N_t-2} \ s_{N_t-1}]^T$.

The model in (7.14) is the well known State-Space model of a communication system over time-varying fading channel.

7.3 Kalman Filter Based Adaptive Detection for DS-CDMA System

In this section we present a first order linear state-space model of a DS-CDMA multiuser channel. We use the Kalman filter for the estimation of channel-distorted received signature sequences. In our proposed receiver structure, the need for training sequence is bound to the startup period only. Later on, receiver adapts itself to the changes of the channel during data transmission depending on previous decisions. Simulation results show that being based on the Kalman filter and of non-gradient nature, our proposed algorithm combats, effectively,
7.3 Kalman Filter Based Adaptive Detection for DS-CDMA System

the time-varying channel impairments and multipath fading effects.

7.3.1 System Model

We assume a synchronous DS-CDMA system with $K$ users and processing gain $N$. The $N \times 1$ received vector is given by \[87, 90\],

$$r(i) = \sum_{k=1}^{K} A_k [H_k^+(i)b_k(i) + H_k^-(i-1)b_k(i-1)]s_k + n(i) \quad (7.15)$$

where

- $b_k(i)$ is the $i$th symbol transmitted by user $k$ with power $E[|b_k(i)|^2] = 1$,
- $s_k$ is $N \times 1$ signature vector of user $k$, 

Figure 7.4: Discrete-time baseband model for synchronous DS-CDMA system
7.3 Kalman Filter Based Adaptive Detection for DS-CDMA System

- $A_k$ is the amplitude of the signal transmitted by user $k$,

- $n(i)$ is the $N \times 1$ white Gaussian noise vector with $\sigma^2 I_N$ covariance matrix,

- $H^+_k(i)$ is $N \times N$ time-varying channel matrix for user $k$ representing the contribution from symbols $b_k(i)$, $k = 1, \cdots, K$.

- $H^-_k(i-1)$ is $N \times N$ time-varying channel matrix for user $k$ representing the inter-symbol interference (ISI) from symbols $b_k(i-1)$, $k = 1, \cdots, K$.

7.3.1.1 Channel Model

The spread symbols for user $k$ in (7.15) are passed through the discrete time-varying channel with impulse response given by the $N \times 1$ vector,

$$h_k(i) = \begin{bmatrix} h_{k,0}(i) & h_{k,1}(i) & h_{k,2}(i) & \cdots & h_{k,L_k-1}(i) & 0 & \cdots & 0 \end{bmatrix}^T$$ (7.16)

where $L_k$ represents the number of paths, assumed to be spaced at the chip duration, $T_c = T/N$, such that $N > L_k$, $T$ is the symbol duration and $(\cdot)^T$ is the matrix transpose operator.

The time-varying channel matrices in (7.15), $H^+_k(i)$ can then be written as [90],

$$H^+_k(i) = \begin{bmatrix} h_k^+(i) & h_k^{+(N-2)}(i) & h_k^{+(N-1)}(i) \end{bmatrix}$$ (7.17)

$$H^-_k(i) = \begin{bmatrix} h_k^-(i) & h_k^{-(N-1)}(i) & h_k^{-(N-3)}(i) & \cdots & h_k^2(i) & h_k^{-1}(i) \end{bmatrix}$$ (7.18)
where $h_k \pm n(i)$ is $h_k(i)$ shifted down (+) or up (-) by $n$ positions, and the vacant positions are filled up with zeros. More conveniently, we can also write the $N \times N$ channel matrices as

$$H_k^+(i) = \begin{pmatrix}
    h_{k,0}(i) & 0 & 0 & \cdots & 0 & 0 \\
    h_{k,1}(i) & h_{k,0}(i) & 0 & \cdots & 0 & 0 \\
    h_{k,2}(i) & h_{k,1}(i) & h_{k,0}(i) & \cdots & 0 & 0 \\
    \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
    h_{k,L_k-1}(i) & h_{k,L_k-2}(i) & h_{k,L_k-3}(i) & \cdots & 0 & 0 \\
    0 & h_{k,L_k-1}(i) & h_{k,L_k-2}(i) & \cdots & 0 & 0 \\
    \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
    0 & 0 & 0 & \cdots & 0 & h_{k,0}(i)
\end{pmatrix} \quad (7.19)$$

$$H_k^-(i) = \begin{pmatrix}
    0 & \cdots & 0 & h_{k,L_k-1}(i) & \cdots & h_{k,2}(i) & h_{k,1}(i) \\
    0 & \cdots & 0 & 0 & \cdots & h_{k,3}(i) & h_{k,2}(i) \\
    \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
    0 & \cdots & 0 & 0 & \cdots & h_{k,L_k-1}(i) & h_{k,L_k-2}(i) \\
    0 & \cdots & 0 & 0 & \cdots & 0 & h_{k,L_k-1}(i) \\
    \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\
    0 & \cdots & 0 & 0 & \cdots & 0 & 0 \\
\end{pmatrix} \quad (7.20)$$

We see that $H_k^-(i)$ is a sparse matrix if $L_k << N$. In order to simplify the derivation and formulation of our estimation algorithm, we will assume that the channel delay spreads are small compared with the symbol duration and, hence, neglect ISI (i.e., $H_k^-(i) = 0$). This is a viable assumption and has also been made in [90]. We, therefore, use $H_k(i)$ to denote the channel matrix for user $k$. The necessary conditions for the optimal signatures presented here can be extended to asynchronous CDMA with ISI by expanding the observation window for the received signal. This complicates the derivations while adding little insight to the synchronous case, so that only synchronous CDMA with negligible ISI is considered throughout the chapter. Rewriting equation (7.15) for synchronous DS-CDMA system over
non-frequency selective fast fading channel, we get

\[ r(i) = \sum_{k=1}^{K} A_k H_k(i) b_k(i) s_k + n(i) \]  \hspace{1cm} (7.21)

We observe that the transmitted signature sequence, \( s_k \), is distorted by the time-varying channel fading channel, \( H_k \); and as a result, channel-distorted version, \( z_k \), of signature sequence is received. We can, therefore, write the received vector as

\[ r(i) = \sum_{k=1}^{K} A_k b_k(i) z_k(i) + n(i) \]  \hspace{1cm} (7.22)

The time-varying received signature vector \( z_k(i) \) is actually the result of convolution between the transmitted signature waveform \( s_k \) and the time-varying channel vector \( h_k(i) \) for user \( k \).

\[ z_k(i) = s_k * h_k(i) \]  \hspace{1cm} (7.23)

\( z_k(i) \) in (7.23) can also be written as

\[ z_k(i) = H_k(i) s_k \]  \hspace{1cm} (7.24)

where \( H_k(i) \) is the channel matrix defined in (7.19). For coherent reception over an ideal time-invariant AWGN channel,

\[ z_k(i) = s_k \]  \hspace{1cm} (7.25)

Fig. 7.4 depicts a synchronous DS-CDMA system [90]. Different from [90], where the channel coefficients have been assumed to be time-invariant, we consider more realistic fast fading time-selective channels.

To account for the dynamic variations that arise in the channel due to the relative motion
between transmitter and receiver, we use the AR model given in (7.11). Because of linear processing between the transmitted signature $s_k$ with power, $s_k^H s_k = 1$ and time-varying channel $h_k(i)$, the transmitted signature $s_k$ deforms to time-varying signature, $z_k(i)$, after passing through time-varying channel. Therefore, we can also write our AR channel model as,

$$z_k(i) = \Xi_k z_k(i - 1) + v(i)$$

(7.26)

where,

$$\Xi_k = \text{diag} [\xi_k, 0, \xi_k, 1, \xi_k, 2, \cdots, \xi_k, N-1]$$

and $v(i) = [v_0(i), v_1(i), v_2(i), \cdots, v_{N-1}(i)]^T$.

Using (7.12), the AR coefficient, $\xi_k$, for user $k$ can be written as,

$$\xi_k = E\{z_{k,i}(i)z_{k,i}^*(i + T)\} = J_0(2\pi f_p T)$$

(7.27)

where $T$ is the symbol duration. $\sigma_v^2$ can be found as given in (7.13).

### 7.3.1.2 Receiver Model

The received signal in (7.21) or (7.22) is the input to a linear filter with coefficients $c_k$. Like in [90], we also consider two types of filters:

1. Coherent RAKE filter (i.e., maximum ratio combiner) or matched filter (MF), given by

$$c_k(i) = \frac{H_k(i)s_k}{\|H_k(i)s_k\|} = \frac{z_k(i)}{\|z_k(i)\|}$$

(7.28)

194
2. An MMSE filter given by

\[ c_k(i) = M^{-1}(i)H_k(i)s_k \]

\[ = M^{-1}(i)z_k(i) \]  

(7.29)

where

\[ M(i) = \sum_{k=1}^{K} A_k^2H_k(i)s_kH_kH_k(i) + \sigma_n^2I_N \]

\[ = \sum_{k=1}^{K} A_k^2z_k(i)z_kH(i) + \sigma_n^2I_N \]  

(7.30)

is the time-varying received covariance matrix and \((\cdot)^H\) denotes the Hermitian transpose.

Thus we can say that our receiver consists of a bank of matched filters as its first part, where we match the received signal vector with the estimated time-varying signature sequence, \(z_k(i)\) of user \(k\). Thus, the output of conventional detector for user \(k\) can then be written as,

\[ y_k(i) = z_kH(i)r(i) \]

\[ = A_kz_kH(i)b_k(i)z_k(i) + \sum_{j \neq k} A_jz_jH(i)b_j(i)z_j(i) + \tilde{n}(i) \]  

(7.31)

where \(\sum_{j \neq k} A_jz_jH(i)b_j(i)z_j(i)\) is the time-varying MAI, which depends on the time-varying channel matrix \(H_k(i)\) for user \(k\) and thus on the quality of the channel estimates or received signature estimates.

In order to detect the transmitted symbols, any of the two filters given in (7.28) and (7.29) can be considered. The former’s output is equivalent to the output of the bank of
matched filters in (7.31). If the latter is considered, then the output of the bank of matched filters in (7.31) is passed to the linear MMSE filter that outputs the following decision for user $k$ [87],

$$
\hat{b}_k(i) = \text{sgn}\left\{ \frac{1}{A_k} \left( M^{-1}(i)z_k^H(i)r(i) \right) \right\} \\
= \text{sgn}\left\{ \left( \sum_{k=1}^{K} A_k^2 z_k(i)z_k^H(i) + \sigma_n^2 \right)^{-1} z_k^H(i)r(i) \right\}
$$

(7.32)

where \(\text{sgn}\) represents the signum function. In this case, we use the time-varying linear transformation on linear MMSE receiver basis, to eliminate the effects of time-varying MAI and noise. As we know, the single-user matched filter receiver is optimized to fight the background white noise, $n(i)$, exclusively, where as the decorrelating detector eliminates the multiuser access interference (MAI) disregarding the background noise. In contrast the MMSE linear detector can be seen as a compromise solution that takes into account the relative importance of each interfering user and the background noise. In fact both the conventional receiver and the decorrelating receiver are the limiting cases of the MMSE linear detector [87].

### 7.3.2 Kalman Filter-Based Signature Sequence Tracking

As mentioned in the previous sections, we base our time-varying signature sequence estimation algorithm on the Kalman filter approach because of its good tracking properties in a highly time-varying environment and its active minimization of estimation error variance [115]. Given the noisy measurements up to the time $i$ in (7.22), and using signature
state equation in (7.26), we have to find the best estimate of \( z_k(i + 1|i) \) which minimizes the error variance. In our case the estimation error vector is equal to the difference between \{True signature vector at time \( i + 1 \)\} and \{Estimated signature vector at time \( i + 1 \) given the measurements up to time \( i \)\},

\[
\tilde{z}_k(i + 1) = z_k(i + 1) - \hat{z}_k(i + 1)
\]

and the estimation error covariance matrix is,

\[
\tilde{P}_k(i + 1) = \text{cov}(\tilde{h}_k(i + 1))
\]

Thus our criterion is given as,

\[
J_k(i + 1) = E\{\tilde{z}_k^H(i + 1)\tilde{z}_k(i + 1)\} = \text{tr}\{\tilde{P}_k(i + 1)\}
\]

The implementation of our adaptive algorithm for signature sequence estimation starts with a training mode that is used to acquire initial \( z_k(i) \) estimates, after which it reverts to a decision-directed mode. In the training mode, the receiver knows the transmitted symbols, whereas in the decision-directed mode, the decoded symbols replace the information symbols. We will focus on the decision-directed mode and assume that initial signature sequence estimates are available through startup training.

Selecting \( z_k(i) = [z_{k,1}(i) \ z_{k,2}(i) \ z_{k,3}(i) \ \cdots \ z_{k,N-1}(i) \ z_{k,N}(i)]^T \) as the state vector, we can exploit equation (7.26) as the state update for user \( k \).
Figure 7.5: Proposed model of the receiver structure for the Kalman filter based adaptive multiuser detection
7.3 Kalman Filter Based Adaptive Detection for DS-CDMA System

7.3.2.1 State-Space Model for the Adaptive Multiuser Detection

From the general form of the State-Space model presented in (7.14), we can re-write our state-space model specifically for the signature sequence estimation case as,

\[
\begin{align*}
\mathbf{z}_k(i + 1) &= \Xi_k \mathbf{z}_k(i) + \mathbf{v}(i + 1) \\
\mathbf{r}(i) &= \sum_{k=1}^{K} A_k b_k(i) \mathbf{z}_k(i) + \mathbf{n}(i)
\end{align*}
\]  

(7.36)

7.3.2.2 Signature Sequence Estimation Algorithm

Our proposed algorithm consists of two parts:

1. Use of training sequence to find optimal signature estimates as a startup

2. To drive algorithm using decisions made in the detection prior to prediction and estimation throughout the process of data transmission.

Various steps involved in our proposed algorithm are elaborated in Fig. 7.5, where the proposed receiver structure for the Kalman filter based adaptive detection of DS-CDMA signals is shown. We can present our signature sequence estimation algorithm based on the state-space model presented in (7.36) in the following steps:

1. Initialize the algorithm with \( \mathbf{z}_k(0|0) \) and \( \mathbf{P}_k(0|0) \).

2. Decode \( \hat{b}_k(i) \) by using (7.32).
3. Obtain Predictions $z_k(i+1|i)$ and $\tilde{P}_k(i+1|i)$ as,

$$z_k(i+1|i) = \Xi_k z_k(i|i) + \sigma_v v(i) \quad (7.37)$$

$$\tilde{P}_k(i+1|i) = \Xi_k \tilde{P}_k(i|i) \Xi_k^H + v(i) \sigma_v^2 v(i)^H \quad (7.38)$$

4. As an innovation step, find $N \times 1$ observation error vector and observation error variance as,

$$e_k(i+1) = r(i) - A_k \tilde{b}_k(i) z_k(i+1|i) \quad (7.39)$$

$$R_{e,k}(i+1) = F_k^H(i) \tilde{P}_k(i+1|i) F_k(i) + \sigma_v^2 I_N \quad (7.40)$$

where $F_k(i) = A_k \tilde{b}_k(i)$ and $\tilde{b}_k(i)$ is found in step 2.

5. Find the Kalman gain as

$$G_k(i+1) = \tilde{P}_k(i+1|i) F_k(i) R_{e,k}^{-1}(i+1) \quad (7.41)$$

6. Correct the estimates made in step 4 as,

$$z_{\hat{b}}(i+1) = z_k(i+1|i+1)$$

$$= z_k(i+1|i) + G_k(i+1) e_k^*(i+1) \quad (7.42)$$

$$\tilde{P}_{\hat{b}}(i+1) = \tilde{P}_k(i+1|i+1)$$

$$= (I_N - G_k(i+1) F_k^H(i)) \tilde{P}_k(i+1|i) \quad (7.43)$$

7. Use real-time corrected $z_k(i+1)$ for the detection of $\tilde{b}_k(i+1)$ and repeat steps 3-7 to estimate and correct the received signature sequence vector at $i+2$ time-instant.
7.3.3 Modes of Operation

Training sequence is usually employed to provide information of the channel to the receiver so that it can get the accurate initial estimates of the signature sequences. Training sequence helps the receiver to quickly adapt itself to the channel conditions. The length of the training sequence is kept as small as possible as no useful information is being conveyed during the training mode. This length is usually equal to the number of iterations required by the receiver to converge to its optimum value. During simulations, the proposed adaptive multiuser detector has been found to converge in about 45 symbols. Thus a training sequence of length 50 is used for subsequent simulations. It is envisaged that this receiver can operate in following four different modes.

7.3.3.1 Decision Directed (DD) mode

In this mode, the receiver operates with Decision feedback only. The initial channel coefficients are assumed arbitrarily. The algorithm finds measurement error vector in (7.39) by using the decision made in the previous iteration. There exists a chance of error propagation, as subsequent decisions are heavily dependent upon the decisions made in earlier iterations.
7.3 Kalman Filter Based Adaptive Detection for DS-CDMA System

7.3.3.2 Training Directed (TD) and DD mode

For overcoming the possibility of error propagation, training can be employed during the convergence time of the algorithm. In this mode, the receiver operates in Training Directed (TD) mode for 50 iterations and then switches to DD mode for the rest of the data transmission.

7.3.3.3 TD and Non-Estimation (NE) mode

In this mode, the receiver operates in TD mode for 50 iterations and then switches to NE mode in which the estimated channel response is kept constant at the last optimized value achieved at the end of TD mode. This mode is similar in analogy to the linear adaptive MMSE receiver, which assumes time-invariant channel.

7.3.3.4 Repeated TD and NE mode

In this mode, the receiver is provided training after short intervals of actual data transmission. The receiver operates in TD mode for 50 iterations and then switches to NE mode for about one frame or block of data symbols. This pattern is repeated till the end of the data transmission. This mode outperforms TD and NE mode but performs worse than TD and DD together and DD alone modes.
7.3.4 Simulation Results

In this section we present numerical results, which illustrate the relative performance of our model. Numerical results are obtained using Monte-Carlo simulation. In each trial of simulation, 5,000 data bits were generated for each user. All users have equal power and undergo independent multipath fading with different multipath gains in their channel impulse responses. The fading coefficients are regenerated with each simulation trial using Jakes’ model [23]. The carrier frequency is 2.4 GHz and the mobile speed is considered 27 Km/h and 99 Km/h taking two different scenarios of Doppler spread (60 and 220 Hz).
7.3 Kalman Filter Based Adaptive Detection for DS-CDMA System

Figure 7.7: The criterion, $J_k(i) = \text{tr}\{\tilde{P}_k(i)\}$, for arbitrary user, $k$, at iteration, $i$

Each user generates bit streams of data with $p(-1) = p(+1) = 1/2$. Random sequences of length 16 are used to spread each data bit of $K$ users. The Signal to Noise ratios ($E_b/N_0$) are set in ascending order from 0 dB to 15 dB.

In Fig. 7.6, Bit Error Rate (BER) is evaluated in each value of $E_b/N_0$ for a population of 4 users, with equal powers and random signature sequences in a fading environment of Doppler spread 60 and 220 Hz, separately. We have considered two multipaths $L_k = 2$, $k = 1, 2, \cdots K$ for each user $k$. The channel coefficients (elements of $h_k$, $k = 1, 2, \cdots, K$) are taken independently and the channel vectors $h_k$ are normalized so that $E\{|h_k|^2\} = 1$. The results show that Doppler spread and multipath fading present a major impeding effect
on the performance of high-speed digital transmission when we don’t consider compensation
for the channel. The results also show that successful estimation of the received signature
waveforms in such a time varying environment leads us to relatively good performance. The
results show that our proposed model outperforms when it is compared to

1. Adaptive MMSE with LMS algorithm [85]
2. RLS
3. Single user bound

all in different Doppler conditions.

Fig. 7.7 shows that convergence of the Kalman filter-based signature sequence estimation
algorithm is very fast compared to other gradient based algorithms (almost two times faster
than LMS based algorithm given in [85]). It also shows that our criterion, \( J_k(i) = \text{tr} \tilde{P}_k(i) \),
discussed in section 7.3.2 is minimized properly which indicates that our estimation process
is running successfully. In our simulations, we have taken initial value of \( \tilde{P}_k(i) \) as 0.05\( I_N \)
for each user with different multipath gains obtained in training. Jazwinski [116] has shown
that the initial statistics, \( \tilde{P}_k(0|0) \), is forgotten as more data are processed. These results
follow from the fact that as long as the filter is stable and the system (state-space model in
(7.36)) is completely controllable and observable then

\[
\lim \tilde{P}_k(i|i) = \hat{P}_k \{\text{very small and constant value}\} \quad \text{as} \quad i \rightarrow \infty \quad (7.44)
\]
Thus the estimation error approaching zero implies that the state estimate converges to the true value given that there exist enough data. The initial estimates will affect the transient performance of the algorithm, since a large initial $P_k(0|0)$ gives a large the Kalman gain, therefore heavily weighting the initial measurements and ignoring the model.

The different modes of operation of linear adaptive CDMA receiver are evaluated over fast fading channel, where the channel conditions are assumed to change in every iteration. The BER performance results for all operation modes are shown in Fig. 7.8. The following observations are made from these results:

1. The BER performance achieved by ‘TD and DD’ mode is the best among all of four modes.

2. In ‘DD alone’ mode, the receiver suffers from error propagation phenomenon, which degrades its performance compared to ‘TD and DD’ mode.

3. In ‘TD and NE’ mode, the receiver performs worst, which means that ordinary CDMA receiver can never cope with the variations in the time-varying channel.

4. The performance improves marginally when the combination of TD and NE mode is repeated after short intervals of iterations, especially before each data block/frame transmission.

The above-mentioned observations indicate that the changing behavior of the channel affects the receiver performance severely whenever channel estimation and compensation is not
Figure 7.8: **BER performance comparison of different operation modes of the Kalman filter-based adaptive CDMA detector, $N = 31$, $K = 4$**

performed. This situation improves when the training is repeated after short intervals. This means that the channel information provided to the receiver by the training sequence in a highly time varying environment is of great help since the channel response is continuously changing. It implies that the receiver continuously needs to perform channel estimation and it cannot just rely on the converged channel response achieved at the end of training. Moreover, when training is not employed at the startup and the algorithm is running in decision directed mode only, there are chances of error propagation. Therefore, it is sometimes required to train the filter before it is run in decision directed mode.
7.4 Conclusions

In this chapter, an autoregressive (AR) model was developed for the time-varying flat fading channel on the basis of its second order fading statistics. The model was then utilized further to establish a linear state-space equation pair for signature sequence adaptation in direct sequence code division multiple access (DS-CDMA) system. Moreover, a decision directed signature sequence estimation algorithm was proposed which worked on an iterative basis during the course of data transmission in a rapidly time-varying environment. The algorithm was based on the proposed state-space model and the Kalman filter so that it could estimate and track the variations in the signature sequence over multipath and time varying fading channels.

The performance of the proposed algorithm was compared with the other adaptive algorithms over time-varying channels and it was found that the proposed algorithm outperforms all other gradient-based algorithms like LMS and RLS, in tracking the rapid changes of the channel. A linear minimum mean squared error (MMSE) detector was used to detect the symbols, which were then exploited in updating the received signature waveforms, distorted by the time-varying channel. Simulation results were presented which showed that the performance of a linear adaptive receiver could be improved significantly with signature tracking on high Doppler spreads in DS-CDMA system. The proposed model can also be extended to eliminate other channel impairments such as CFO (Carrier Frequency Offset) in OFDM systems.
Chapter 8

Conclusions and Future Work

This chapter first gives a brief summary of the thesis in section 8.1 and then discusses final conclusions and future research work based on the results of this dissertation in section 8.2.
8.1 Summary of the Thesis

In Chapter 2, we have addressed the issue of physical channel modeling for the cellular mobile communication system. We have extensively studied the previous approaches used for modeling cellular mobile channel in picocell, microcell, and macrocell environments. We have developed necessary channel modeling parameters and proposed a generalized physical channel model, referred to as the ‘Eccentro-Scattering Model’. This model can be applied to any type of cellular environment with appropriate choice of eccentricity, semi-major axis, and distribution of scatterers around MS and/or BS. We have also introduced a more practical scattering model, the Jointly Gaussian Scattering Model (JGSM), which consists of two Gaussian functions each for the distribution of scatterers around BS and MS. The same methodology can also be used to develop a generalized spatial channel model for a 3-D environment.

In Chapter 3, we have studied the spatial characteristics of cellular mobile channel for picocell, microcell, and macrocell environments assuming uniform and Gaussian distribution for the scatterers. Utilizing the Eccentro-Scattering Model and JGSM, we have derived general expressions for the pdf of AoA of the multipath signals at BS. The derived results show that the previous spatial models can easily be extracted from our proposed model with appropriate selection of parameters. We have thoroughly discussed the results and compared them with those of all existing models. The theoretical results are also compared with some available measurements both in indoor and outdoor environments. The resulting compar-
8.1 Summary of the Thesis

Comparisons show good agreement with the realistic situations. We can thus assume our proposed model to be useful in simulating several propagation scenarios for wireless communications systems. The derived results, in closed form, can also be used in further research work to model Doppler characteristics and tracking properties of time-varying fading channels.

In Chapter 3, we have also addressed the issue of the impact of local-to-BS scattering on the spatial characteristics and implemented JGSM for low antenna-height urban environment by introducing an adjustable scattering-free region around BS. The adjustable scattering-free region around BS models the extent of scattering in the vicinity of BS and thus can easily be used as a control-valve for the inclusion/exclusion of scattering objects in the vicinity of BS according to their anticipated effect on the angular distribution of the cellular mobile channel. We have found that the JGSM along with the provision of scattering-free region provides good fitness to the field measurements when compared with all existing Gaussian scattering models that consider only one Gaussian function for the distribution of scatterers around MS.

In Chapter 4, we have proposed a novel generalized method of quantifying the angle spread of the multipath power distribution. The proposed method provides almost all parameters associated to the angular spread, which can be further used for calculating more accurate spatial correlations of the multipath fading channels. The proposed parameters are also useful in finding the exact standard deviation of the truncated angular distributions and the angular data acquired in measurement campaigns. The degree of accuracy in correlation
calculations can lead to the computation of exact separations among array elements needed for diversity antennas. Currently, truncated Gaussian or Laplacian functions are often used to represent the azimuthal distribution of multipath signals. Such functions usually simplify the calculations of correlation in MIMO channels. We have indicated that the use of standard deviation of full-span functions as the standard deviation of the truncated function causes severe effects on the angle spread, which in turn distorts the accuracy of correlation figures in MIMO channels. Due to the importance of angle spread in the fading statistics, we have proposed its use as the goodness-of-fit measure in measurement campaigns. The proposed method of quantifying angle spread can thus be used in finding the accurate separations among array elements in outdoor MIMO systems where measurement campaigns provide basis for channel models.

In Chapter 5, we have discussed the temporal characteristics of cellular mobile channel in picocell, microcell, and macrocell environments. We have employed the proposed Eccentro-Scattering model to derive the pdf of ToA of the multipath signal for these cellular environments. In macrocell environment, our model incorporated the effect of distant scatterers, far from BS and MS on the temporal dispersion of the multipath signal in addition to that of local scatterers. A simplified generic closed-form formula for the pdf of ToA due to local scatterers has been derived, from which previous models can be easily reproduced. The presented formulas can be used to simulate temporal dispersion of the multipath channel in a variety of propagation conditions. Furthermore, these formulas are also helpful in designing efficient equalizers to combat intersymbol interference (ISI) for frequency-selective
8.1 Summary of the Thesis

In Chapter 6, we have investigated the effects of mobile motion on the spatial and temporal statistics of the cellular mobile channel. We have discussed several motion scenarios that are responsible for such effects. We have formulated the changes in the AoA and ToA distributions of the multipath signals at BS during the course of MS motion for different cellular environments. We have plotted the behavior of all important spatial and temporal statistical parameters under the effect of mobile motion. The proposed theoretical results in spatial characteristics can be extended to characterizing and tracking transient behavior of Doppler spread in time-varying fast fading channels; likewise the proposed theoretical results in temporal characteristics can be utilized in designing efficient equalizers for combating inter-symbol interference (ISI) in time-varying frequency-selective fading channels.

In Chapter 7, an autoregressive (AR) model was developed for the time-varying flat fading channel on the basis of its second order fading statistics. The model was then utilized further to establish a linear state-space equation pair for signature sequence adaptation in DS-CDMA systems. Moreover, a decision directed signature sequence estimation algorithm was proposed which worked on iterative basis during the course of data transmission in a rapidly time-varying environment. The algorithm was based on the proposed state-space model and the Kalman filter so that it could estimate and track the variations in the signature sequence over multipath and time varying fading channel.

The performance of the proposed algorithm was compared with the other adaptive algo-
8.2 Conclusions and Future Work

This research has studied spatial channel models for cellular mobile systems and their use in the characterization of multipath fading channels. The results were presented mainly in five parts; a) modeling of scattering mechanisms, b) derivation of the closed-form expressions for the spatio-temporal characteristics, c) generalization of the quantitative measure of angular spread, d) investigation of the effect of mobile motion on the spatio-temporal characteristics, and e) characterization of fast fading channel and its use in signature sequence adaptation for DS-CDMA system.

The results presented in this work have implications to cellular wireless system design, depicted in Fig. 1.5 of Chapter 1. The analytical results for the distributions of the angle and time of arrival of multipath signals can be useful for the purposes of system design.
and performance evaluation in cellular systems. The generalized quantitative definition of
the angular spread proposed in the work will be used for calculating more accurate spatial
correlations and thus the exact separation distances between array elements required for
maximizing capacity in MIMO systems or diversity antennas. For the first time, angular
spread was proposed as the goodness-of-fit measure in angular measurement campaigns based
on its key role in the fading processes. The behavior of some important spatial and temporal
statistical parameters was investigated under the effect of mobile motion. The results, in
closed mathematical form in this regard, can be useful in studying the behavior of time-
varying frequency-selective fading channels. In the last part of the thesis, a Kalman filter
based adaptive DS-CDMA receiver structure was proposed, where the simulation results
showed that the performance of a linear adaptive receiver could be improved significantly
with signature tracking on high Doppler spreads in DS-CDMA systems.

Besides the use of Fig. 1.5 of Chapter 1 in proposing the methodology of our dissertation,
it is also helpful in introducing the strategy of our future research work. This strategy can
be grouped according to the following three plans:

Plan 1

The general formulas derived for the pdf of AoA of the multipath signals at BS in (3.10),
(3.17), (3.27), (3.31), and (3.41) provide almost all information needed for calculating the
spatial correlations among the antenna elements of MIMO arrays. We are thus planning to
8.2 Conclusions and Future Work

use these formulas along with the angular spread quantifiers, discussed in Chapter 4, to find:

1. the spatial correlations among antenna elements of MIMO arrays which are responsible to decrease MIMO system capacity,

2. the exact separations between the antenna elements required to maximize MIMO capacity,

3. the design parameters, needed for diversity antenna to overcome deep fades at BS antennas.

Plan 2

The general formulas derived for the pdf of ToA in Chapter 5, can be further extended to finding coherence bandwidth, which is an important parameter in the designing mechanism of channel equalizers. ToA distributions of Chapter 5 and temporal spread parameters of Chapter 6 are also helpful in designing RAKE receiver fingers for CDMA and W-CDMA multiuser detectors. If we apply the RAKE finger number decision rule, given in [117, 118] and finger assignment algorithm, discussed in [119] on the general expressions of the pdf of ToA in (5.15), (5.27) and (5.39), we will certainly approach a generalized RAKE receiver finger number selection criteria for all cellular environments, according to their local terrain and clutter.
8.2 Conclusions and Future Work

Plan 3

In Chapter 7, a state-space model was developed on the basis of the second order fading statistics of the time-varying channel. The model was flexible to be used for any type of cellular environment by simply changing the parameters of the AoA distribution in (7.6) and (7.7). However, for the simplicity of theoretical results, an isotropic scattering environment was considered. As we have discussed in detail in Chapter 1 that in modern communication systems, antenna arrays are usually used on both link ends, which adds directionality to the MS. In such cases, the state-space model can be modified by using the effects of induced directionality on the fading statistics. Such effects are studied in [26,120–122]. Spatial correlations in non-isotropic scenarios are also discussed extensively in [123,124]. However, to the best of our knowledge, there is no inclusive time-varying channel estimation model available in the literature which can be able to accommodate the directionality induced by MS antennas. Therefore, the state-space modeling approach discussed in Section 7.2 of Chapter 7, can easily be extended to non-isotropic scattering scenarios.
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