# Contents

Acknowledgements                                      v  
Abstract                                               vi  
List of Figures                                        xv  
List of Tables                                         xviii  
List of Abbreviations                                 xix  
Glossary                                              xx  

## 1. Introduction

- Challenges in uncoded Multi-Antenna Systems-         3  
- Approach to Optimize MIMO Detection-                   4  
- Exact Solution in a Coded Multi-Antenna System       5  
- Orthogonal Coded Spatial Multiplexing System         6  
- Organization of Thesis                                 6  

## 2. Multipath Fading Channels, Modulation Techniques and Antenna Diversity

- Introduction                                            8  
- Channel Characterizations                              8  
  - Large Scale Propagation Models                        9  
    - Deterministic Approach                              9  
      (a) Free Space Propagation Model                     9  
      (b) Long-Distance path loss Model                    10  
  - Stochastic Approach                                   10  
    (a) Lognormal Shadowing Model                         10  


### 2.2.2 Small Scale Propagation Models

#### 2.2.2.1 Mobile Multipath channels parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fading</td>
<td>12</td>
</tr>
<tr>
<td>Doppler Shift</td>
<td>12</td>
</tr>
<tr>
<td>Power Delay Profile $\Phi_c(\tau)$</td>
<td>12</td>
</tr>
<tr>
<td>Excess Delay</td>
<td>13</td>
</tr>
<tr>
<td>Delay Spread ($T_m$)</td>
<td>13</td>
</tr>
<tr>
<td>Coherent Bandwidth ($BW_c$)</td>
<td>13</td>
</tr>
<tr>
<td>Doppler Spread ($B_D$)</td>
<td>13</td>
</tr>
<tr>
<td>Coherent Time ($T_c$)</td>
<td>14</td>
</tr>
</tbody>
</table>

#### 2.2.2.2 Types of Small-Scale Fading

<table>
<thead>
<tr>
<th>Type</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat Fading</td>
<td>14</td>
</tr>
<tr>
<td>Frequency-Selective Fading</td>
<td>14</td>
</tr>
<tr>
<td>Fast Fading</td>
<td>15</td>
</tr>
<tr>
<td>Slow Fading</td>
<td>15</td>
</tr>
</tbody>
</table>

#### 2.2.2.3 Statistical Models of Small-Scale Propagation Channels

<table>
<thead>
<tr>
<th>Model</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rayleigh Fading Channel</td>
<td>15</td>
</tr>
<tr>
<td>Ricean Fading Channel</td>
<td>16</td>
</tr>
<tr>
<td>Nakagami Fading Channel</td>
<td>16</td>
</tr>
</tbody>
</table>

#### 2.2.2.4 Statistical Models for Multipath Fading Channels

<table>
<thead>
<tr>
<th>Model</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>TwoRay Model</td>
<td>17</td>
</tr>
<tr>
<td>Markov Channel Modeling</td>
<td>17</td>
</tr>
<tr>
<td>Finite State Markov Channel</td>
<td>17</td>
</tr>
<tr>
<td>Hidden Markov Models</td>
<td>19</td>
</tr>
</tbody>
</table>

#### 2.2.2.5 Multi-Input Multi-Output Channel Model

<table>
<thead>
<tr>
<th>Model</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matrix Channel Model</td>
<td>20</td>
</tr>
<tr>
<td>Physical Scattering Model</td>
<td>22</td>
</tr>
</tbody>
</table>

### 2.3 Modulation Techniques

#### 2.3.1 Classification of Modulation Schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Page</th>
</tr>
</thead>
</table>

#### 2.3.2 Selection of Digital Modulation Schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Page</th>
</tr>
</thead>
</table>

#### 2.3.3 Different Modulation Schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Page</th>
</tr>
</thead>
</table>

#### 2.3.3.1 Linear Modulation Schemes

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Page</th>
</tr>
</thead>
</table>
2.3.3.2 Constant Envelope Modulation Schemes  -  -  24
2.3.3.3 Combining Linear and Constant Envelope Modulation  24
   (a) M-ary Phase Shift Keying (MPSK)  -  -  25
   (b) Quadrature Amplitude Modulation (MQAM)  26
2.3.3.4 Spread Spectrum Modulation Techniques  -  -  27
2.3.3.5 Orthogonal Frequency Division Multiplexing  -  29

2.4 Diversity  -  -  -  -  -  -  -  -  -  -  32
2.4.1 Diversity Techniques  -  -  -  -  -  -  -  -  -  -  32
   2.4.1.1 Spatial Diversity  -  -  -  -  -  -  -  -  -  -  32
   2.4.1.2 Polarization Diversity  -  -  -  -  -  -  -  -  -  -  33
   2.4.1.3 Frequency Diversity  -  -  -  -  -  -  -  -  -  -  33
   2.4.1.4 Time Diversity  -  -  -  -  -  -  -  -  -  -  33
2.4.2 Diversity Combining Methods  -  -  -  -  -  -  -  -  -  -  34
   2.4.2.1 Selection Combining  -  -  -  -  -  -  -  -  -  -  34
   2.4.2.2 Maximum Ratio Combining  -  -  -  -  -  -  -  -  -  -  34
   2.4.2.3 Equal Gain Combining  -  -  -  -  -  -  -  -  -  -  35

2.5 Summary  -  -  -  -  -  -  -  -  -  -  36

3. Multiple Antennas Communication Systems  -  -  -  -  -  37
3.1 Introduction  -  -  -  -  -  -  -  -  -  -  37
3.2 Narrowband MIMO  -  -  -  -  -  -  -  -  -  -  37
3.3 MIMO Channel Decomposition  -  -  -  -  -  -  -  -  -  -  39
3.4 MIMO Channel Capacity  -  -  -  -  -  -  -  -  -  -  41
   3.4.1 Static Channels  -  -  -  -  -  -  -  -  -  -  41
      3.4.1.1 Perfect Channel Knowledge at Transmitter  -  -  -  42
      3.4.1.2 Channel unknown at Transmitter  -  -  -  -  43
3.4.2 Fading Channels  -  -  -  -  -  -  -  -  -  -  44
   3.4.2.1 Perfect Channel Knowledge at Transmitter  -  -  -  44
   3.4.2.2 Channel unknown at Transmitter  -  -  -  -  44
   3.4.2.3 Channel unknown at Transmitter and Receiver  -  -  -  46
3.5 Space-Time Coding  -  -  -  -  -  -  -  -  -  -  46
   3.5.1 General Matrix for Orthogonal Space-Time Codes  -  -  -  46
### 3.5.2 A Simple Space-Time Block Coded system - - - - 48
3.5.2.1 The Transmission Model - - - - 48
3.5.2.2 ML Decoding of O-STBC over Quasi-Static Channel 48
3.5.2.3 Quasi-Static Channel - - - - 50
### 3.5.3 Other Space-Time Block Codes - - - - 52
### 3.5.4 Spatial Multiplexing and BLAST Architecture - - 53
### 3.6 Frequency-Selective MIMO Channels - - - - 55
### 3.7 Summary - - - - - - 56

### 4. Symbol Detection in MIMO System - - - - - - 57
4.1 Introduction - - - - - - - 57
4.2 MIMO System Model - - - - - - - 57
4.3 MIMO Detection Problem Formulation - - - - - 58
4.4 Existing MIMO Detection Algorithms - - - - - - 59
4.4.1 Sphere Decoder - - - - - - - 60
4.4.2 Linear Detection - - - - - - - 62
4.3.2.1 Zero-forcing Detection - - - - - - 62
4.3.2.2 Minimum Mean Square Error Detection - - - - - 63
4.4.3 Non-linear (V-BLAST) Detection - - - - - 64
4.4.4 ZF-ML Detection - - - - - - - 66
4.4.5 SDP Detection - - - - - - - 67
4.5 Summary - - - - - - - 68

### 5. Meta-heuristic Techniques - - - - - - - 69
5.1 Introduction - - - - - - - 69
5.2 Meta-heuristics and heuristics - - - - - - 69
5.3 Natural Optimization by Ants - - - - - - 71
5.4 Ant Colony Optimization Algorithm - - - - - - 72
5.5 Binary Ant System (BAS) - - - - - - 73
5.6 Natural Optimization by Swarm - - - - - - 74
5.7 Particle Swarm Optimization Algorithm - - - - - 75
5.8 Summary - - - - - - - 80
6. Swarm Intelligence Meta-heuristics for Symbol Detection in MIMO System 81
   6.1 Introduction - - - - - - - - 81
   6.2 BA-MIMO Detection Algorithm - - - - - - 81
   6.3 Performance analysis of BA-MIMO Detection- - - - - 82
   6.4 Computational Complexity Comparison - - - - - 85
   6.5 Performance-Complexity trade-off - - - - - 86
   6.6 Discussion - - - - - - - - 87
   6.7 PSO-MIMO Detection Algorithm - - - - - - 87
   6.8 SPSO-MIMO Detection Algorithm - - - - - - 88
   6.9 MPSO-MIMO Detection Algorithm - - - - - - 89
   6.10 BPSO-MIMO Detection Algorithm - - - - - - 90
   6.11 PSO Parameter Control - - - - - - - - 91
   6.12 PSO-MIMO Detection Algorithm’s Relationship - - - - 92
   6.13 Simulation Results and Performance Analysis - - - - 92
      6.13.1 Experimental Setup - - - - - - - - 92
      6.13.2 BER versus SNR Performance - - - - - 93
      6.13.3 Computational Complexity Theoretical Evaluation - - 95
      6.13.4 BER Performance-Computational Complexity Trade-off - 98
      6.13.5 Effects of Change in Algorithms Parameters and Iterations - 99
      6.13.6 Effect of initial guess on the performance - - - - 100
      6.13.7 Comparison of different PSO-MIMO Detection Techniques- 101
      6.13.8 An Analysis of PSO Algorithm as a MIMO Detection Technique 101
      6.13.9 Discussion - - - - - - - - 101
   6.14 Fitness Landscape Analysis of MIMO Detection Problem - - - 102
   6.15 Conclusions - - - - - - - - 105

7. Symbol Detection in Coded Multi-antenna Systems - - - - 106
   7.1 Introduction - - - - - - - - 106
   7.2 Space-Time Block Codes - - - - - - - - 107
      7.2.1 STBC with two transmit antennas - - - - - - - - 107
         7.2.1.1 Conventional Maximum Likelihood Detection - - 108
         7.2.1.2 Simplified Maximum Likelihood Detection - - 109

xii
9.2 Future Work - - - - - - - - 137

A. List of Papers from the Research Work Conducted - - - 138

References 140