Contents

Preface xi

CHAPTER 1
Introduction 1
1.1 Fundamentals and Terms 1
  1.1.1 Basic Measurements 2
  1.1.2 Terms 3
1.2 Applications 4
  1.2.1 Cellular Networks 4
  1.2.2 Person and Asset Tracking 5
  1.2.3 Wireless Network Security 6
  1.2.4 Location-Based Advertising 6
  1.2.5 Location Services for Vehicles and Traffic 6
1.3 Overview of Distance Measurement and Location Methods 6
1.4 Organization of the Book 10
References 11

CHAPTER 2
Basic Principles and Applications 13
2.1 Signal Parameters 14
  2.1.1 Time Resolution 14
  2.1.2 Pulse Width and Duty Cycle 15
  2.1.3 Bandwidth 15
  2.1.4 Noise 17
  2.1.5 Pulse Compression 20
2.2 Basics of Location 27
  2.2.1 Rho-Theta 27
  2.2.2 Theta-Theta or AOA 28
  2.2.3 Rho-Rho or TOA 29
  2.2.4 TDOA and Hyperbolic Curves 30
2.3 Navigation Systems 32
  2.3.1 DME 33
  2.3.2 VOR 37
  2.3.3 Loran-C 38
  2.3.4 GPS 44
2.4 Conclusions 51
References 52
CHAPTER 5  
Multicarrier Phase Measurement  107
5.1 Principle of Multicarrier Phase Measurement  107
5.2 Phase Slope Method  108
5.3 Phase Error Versus Signal-to-Noise Ratio  111
5.4 Estimation of Distance Variance Versus SNR  115
5.5 Multipath  118
5.6 System Implementation  123
5.6.1 Phase Difference Measurements and Analogy to TDOA  125
5.7 OFDM  126
5.7.1 The Basics of OFDM  126
5.7.2 OFDM Distance Measurement  130
5.7.3 Location Based on OFDM Distance Measurement  134
5.7.4 Resolution of OFDM Distance Measurement  136
5.8 Conclusions  137
References  138

CHAPTER 6  
Received Signal Strength  139
6.1 Advantages and Problems in RSS Location  139
6.2 Propagation Laws  140
6.2.1 Free Space  140
6.2.2 Free-Space dB  140
6.2.3 Open Field  141
6.2.4 Logarithmic Approximation  142
6.2.5 Randomizing Term X  143
6.2.6 Outdoor Area Networks  144
6.2.7 Path Loss and Received Signal Strength  146
6.3 RSS Location Methods  146
6.3.1 RSS Location from Range Estimations  146
6.3.2 RSS Location Based on Database Comparison  147
6.4 Conclusions  158
References  158

CHAPTER 7  
Time of Arrival and Time Difference of Arrival  161
7.1 TOA Location Method  162
7.1.1 Overdetermined TOA Equation Solution  163
7.1.2 TOA Method in GPS Positioning  166
7.2 TDOA  170
7.2.1 TDOA Measurement Techniques  171
7.2.2 Multilateral and Unilateral Topologies for TDOA  173
7.2.3 TDOA Geometric Model  175
7.2.4 TDOA Example  177
### 7.3 Performance Impairment

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3.1 Uncertainties in Data Measurement</td>
<td>181</td>
</tr>
<tr>
<td>7.3.2 Random Noise</td>
<td>182</td>
</tr>
<tr>
<td>7.3.3 Dilution of Precision (DOP)</td>
<td>182</td>
</tr>
<tr>
<td>7.3.4 Multipath</td>
<td>184</td>
</tr>
<tr>
<td>7.3.5 Cochannel Interference</td>
<td>186</td>
</tr>
</tbody>
</table>

### 7.4 Conclusions

References 186

### CHAPTER 8

**Angle of Arrival**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1 Triangulation</td>
<td>189</td>
</tr>
<tr>
<td>8.2 Antenna Performance Terms and Definitions</td>
<td>191</td>
</tr>
<tr>
<td>8.3 Finding Direction from Antenna Patterns</td>
<td>194</td>
</tr>
<tr>
<td>8.4 Direction-Finding Methods</td>
<td>198</td>
</tr>
<tr>
<td>8.4.1 Amplitude Comparison</td>
<td>198</td>
</tr>
<tr>
<td>8.4.2 Phase Interferometer</td>
<td>200</td>
</tr>
<tr>
<td>8.5 Electronically Steerable Beam Antennas</td>
<td>207</td>
</tr>
<tr>
<td>8.6 ESPAR Antenna Array</td>
<td>214</td>
</tr>
<tr>
<td>8.7 Conclusions</td>
<td>220</td>
</tr>
</tbody>
</table>

### CHAPTER 9

**Cellular Networks**

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.1 Cellular Location-Based Services</td>
<td>223</td>
</tr>
<tr>
<td>9.2 Cellular Network Fundamentals</td>
<td>224</td>
</tr>
<tr>
<td>9.2.1 GSM Transmissions</td>
<td>226</td>
</tr>
<tr>
<td>9.2.2 CDMA</td>
<td>227</td>
</tr>
<tr>
<td>9.2.3 UMTS</td>
<td>228</td>
</tr>
<tr>
<td>9.3 Categories of Location Systems</td>
<td>229</td>
</tr>
<tr>
<td>9.4 GPS Solution</td>
<td>230</td>
</tr>
<tr>
<td>9.5 Cell-ID</td>
<td>231</td>
</tr>
<tr>
<td>9.6 Location Technologies Using TDOA</td>
<td>232</td>
</tr>
<tr>
<td>9.6.1 Enhanced Observed Time Differences</td>
<td>234</td>
</tr>
<tr>
<td>9.6.2 Observed Time Difference of Arrival</td>
<td>235</td>
</tr>
<tr>
<td>9.6.3 Uplink Time Difference of Arrival</td>
<td>236</td>
</tr>
<tr>
<td>9.7 Angle of Arrival</td>
<td>236</td>
</tr>
<tr>
<td>9.8 Received Signal Strength and Pattern Recognition</td>
<td>236</td>
</tr>
<tr>
<td>9.9 Problems and Solutions in Cellular Network Positioning</td>
<td>237</td>
</tr>
<tr>
<td>9.9.1 Narrowband Networks</td>
<td>237</td>
</tr>
<tr>
<td>9.9.2 CDMA</td>
<td>237</td>
</tr>
<tr>
<td>9.9.3 GSM</td>
<td>238</td>
</tr>
<tr>
<td>9.10 Handset-Based Versus Network-Based Systems</td>
<td>238</td>
</tr>
<tr>
<td>9.11 Accuracy Factors</td>
<td>239</td>
</tr>
<tr>
<td>9.12 Conclusions</td>
<td>239</td>
</tr>
</tbody>
</table>

References 240
CHAPTER 10
Short-Range Wireless Networks and RFID 241
10.1 WLAN/WIFI 242
  10.1.1 TOA 242
  10.1.2 TDOA Methods for WLAN Location 248
  10.1.3 Fingerprinting 249
10.2 WPAN 251
  10.2.1 Bluetooth 251
  10.2.2 ZigBee 255
  10.2.3 Alternate Low Rate WPAN Physical Layer IEEE 802.15.4a 257
  10.2.4 ECMA-368 Standard 258
10.3 RFID 259
  10.3.1 Proximity Location 260
  10.3.2 Distance Bounding for Security 260
  10.3.3 Accurate RFID Location 262
10.4 Conclusions 262
  References 263

CHAPTER 11
Ultra-wideband (UWB) 265
11.1 Telecommunication Authority Regulations 265
  11.1.1 FCC Regulations 265
  11.1.2 UWB in the European Community 267
11.2 UWB Implementation 268
  11.2.1 Impulse Radio UWB 268
  11.2.2 OFDM 272
11.3 IEEE 802.15.4a 274
  11.3.1 Physical Layer Characteristics and Synchronization 274
  11.3.2 Ranging Protocol 280
11.4 Dealing with Multipath and Nonline of Sight 283
  11.4.1 Multipath 283
  11.4.2 Nonline of Sight 284
11.5 Conclusions 286
  References 286

Bibliography 289

List of Acronyms and Abbreviations 293

About the Author 297

Index 299