Channel Characterisation and Error-Control Optimisation for Satellites in Low Earth Orbit

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by

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ABSTRACT

This thesis describes the in-orbit measurements, design and simulation of error-control strategies and channel modelling for low-Earth orbiting satellites, specifically in a restrictive small satellite platform. The motivation to pursue such a direction is the quest to optimise the low-Earth orbit (LEO) satellite communication link. Until a few years ago, advanced designs for satellite communications systems had focused on conventional geostationary Earth orbit (GEO) communication technologies which are not necessarily tailored to the LEO environment. Such sub-optimal designs were accommodated by the typical application of LEO satellites - remote sensing satellites - normally being large satellites equipped with huge parabolic dishes. With the recent rapid development in numerous LEO satellite constellations and trend in the satellite industry towards smaller and affordable satellites, the prominence of satellites in LEO cannot be ignored and it has become crucial to efficiently utilise the communications link.

Until now, a suitable channel model for low-Earth orbit satellites has not existed. In order to provide a viable satellite network, a proper knowledge of the dynamic characteristics of the link is essential. A UHF measurement campaign from the UoSAT-3 microsatellite in LEO was therefore undertaken and analysis of the error statistics provides unique information on the channel behaviour for a broad range of elevation angles. The thesis has investigated generative Markov models as a means of representing the observed error statistics and established that the LEO satellite channel can be accurately described by a multiple-good-state, one-error state Fritchman model, or a four-state Markov model under special circumstances which are outlined.

Various error control strategies have been evaluated based on the in-orbit measured data and proposed channel models, therefore verifying the precision of the Fritchman and four-state Markov models. During the course of this work, two schemes comprising type-II hybrid-ARQ based on punctured Reed Solomon codes and byte interleaving were investigated and the tradeoffs were identified. A novel type-II + delay hybrid protocol has been proposed and has been demonstrated to provide further increases in throughput performance.

The principal conclusion from this thesis is that, using the results of the measurement campaign with an in-orbit satellite, it has been possible to generate a realistic fading model for use in future planning for LEO satellite systems. Furthermore, the type-II, type-II+delay hybrid and byte interleaving techniques are shown to provide an improvement in throughput performance of the existing store-and-forward communications protocol with varying tradeoffs between the techniques.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>ii</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF GRAPHS</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>x</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>xii</td>
</tr>
</tbody>
</table>

## Chapter 1: Low Earth Orbit Satellite Communications

1.1 INTRODUCTION .................................................................................. 1-1
1.2 OBJECTIVES AND SCOPE ................................................................... 1-3
1.3 STRUCTURE OF THE THESIS .............................................................. 1-4
1.4 REFERENCES...................................................................................... 1-5

## Chapter 2: The Specifics Of Small Satellites In Low Earth Orbit

2.1 INTRODUCTION .................................................................................. 2-1
2.2 THE CHOICE OF ORBIT ...................................................................... 2-2
  2.2.1. Communication Statistics ...................................................... 2-2
  2.2.2. Doppler Shift ......................................................................... 2-3
  2.2.3. Variations In Free Space Loss .............................................. 2-3
2.3 THE CHOICE OF FREQUENCY ................................................................ 2-4
2.4 THE CHOICE OF ANTENNA .................................................................. 2-4
2.5 RADIOWAVE PROPAGATION EFFECTS .................................................... 2-5
  2.5.1. Ionospheric Scintillation ...................................................... 2-6
  2.5.2. The Faraday Effect .................................................................. 2-6
  2.5.3. Tropospheric Scintillation ..................................................... 2-7
  2.5.4. Gaseous And Hydrometeor Attenuation .................................... 2-7
  2.5.5. Multipath Fading .................................................................... 2-7
  2.5.6. Depolarisation ....................................................................... 2-8
  2.5.7. Noise And Interference .......................................................... 2-8
2.6 THE MICROSATELLITE STRUCTURE ..................................................... 2-9
  2.6.1. Spacecraft Size ..................................................................... 2-9
  2.6.2. Power Onboard ...................................................................... 2-9
  2.6.3. Choice Of Attitude Control ................................................... 2-10
2.7 SUMMARY .......................................................................................... 2-11
2.8 REFERENCES...................................................................................... 2-11

## Chapter 3: Low Earth Orbit Channel Measurements And Channel Characterisation

3.1 INTRODUCTION .................................................................................. 3-1
3.2 FADING CHANNELS ........................................................................... 3-2
  3.2.1. The Terrestrial Environment .................................................... 3-3
  3.2.2. The Mobile Satellite Channel .................................................. 3-4
3.3 LITERATURE REVIEW ON CHANNEL CHARACTERISATION TECHNIQUES .... 3-5
3.4 LOW EARTH ORBIT UHF MEASUREMENT CAMPAIGN ............................. 3-7
  3.4.1. Average Bit Error Rate .......................................................... 3-10
  3.4.2. Burst Distribution .................................................................... 3-10
  3.4.3. Burst Interval (Or Gap) Distribution ....................................... 3-10
  3.4.4. Error-Free Run Distribution ................................................... 3-11
  3.4.5. Gap-Between -Errors Distribution .......................................... 3-11
3.5 STATISTICS OF LEO UHF BURST CONDITIONS ................................... 3-12
  3.5.1. Histograms of burst lengths and burst gaps .............................. 3-12
  3.5.2. Average Bit Error Rate .......................................................... 3-17
  3.5.3. Cumulative histograms of burst lengths and burst gaps .............. 3-18
Chapter 4: The Data Link Layer - Protocol Design Issues And Error Control Techniques

4.1 INTRODUCTION .................................................................................. 4-1
4.2 THE PACSAT PROTOCOL SUITE ....................................................... 4-3
  4.2.1. PACSAT Broadcast Protocol ....................................................... 4-3
  4.2.2. AX.25 Data Link Layer Protocol .............................................. 4-5
4.3 IMPROVEMENTS TO CURRENT PROTOCOL ..................................... 4-6
4.4 HYBRID-ARQ SCHEMES ................................................................ 4-6
  4.4.1. Type-I hybrids ........................................................................... 4-8
  4.4.2. Type-II hybrids ......................................................................... 4-8
  4.4.3. Code Combining ........................................................................ 4-9
  4.4.4. Diversity Combining ................................................................. 4-9
4.5 TYPE-II HYBRID BASED ON PUNCTURED RS CODES ................. 4-10
  4.5.1. Basic properties of RS codes ..................................................... 4-10
  4.5.2. Punctured RS codes ................................................................. 4-11
4.6 INTERLEAVING .................................................................................. 4-13
4.7 THE FEEDBACK CHANNEL .............................................................. 4-14
4.8 OPNET SIMULATION TOOL ............................................................ 4-15
  4.8.1. The Network ............................................................................. 4-16
  4.8.2. The Nodes ................................................................................ 4-16
  4.8.3. The LEO communications link ................................................. 4-16
  4.8.4. The Process Domain ................................................................. 4-17
4.9 THE SELECTIVE REPEAT PROTOCOL DESIGN ISSUES ............... 4-18
  4.9.1. Event NetworkLayerReady ...................................................... 4-19
  4.9.2. Event FrameArrival .................................................................. 4-20
  4.9.3. Event CksumError ................................................................... 4-20
  4.9.4. Event NetworkIdle ................................................................. 4-20
  4.9.5. Event Timeout ......................................................................... 4-21
4.10 SUMMARY ....................................................................................... 4-21
4.11 REFERENCES ................................................................................... 4-22

Chapter 5: The Performance Of Error Control Strategies

5.1 INTRODUCTION .................................................................................. 5-1
5.2 GENERAL CONSIDERATIONS IN TRADE-OFFS .............................. 5-2
5.3 EVALUATING THE ACCURACY OF MODELS AGAINST CODING PERFORMANCE ........................................................................ 5-3
  5.3.1. Model comparisons at 15° ........................................................ 5-4
  5.3.2. Model comparisons at 23° ........................................................ 5-5
  5.3.3. Model comparisons at 30° ........................................................ 5-6
  5.3.4. Model comparisons at 40° ........................................................ 5-6
  5.3.5. Model comparisons at 52° ........................................................ 5-6
  5.3.6. Model comparisons at 63° ........................................................ 5-7
  5.3.7. Model comparisons at 68° ........................................................ 5-7
  5.3.8. Model comparisons at 74° ........................................................ 5-7
5.4 TYPE-II HYBRID PERFORMANCE .................................................. 5-8
  5.4.1. Type-II Performance at 15° ....................................................... 5-8
  5.4.2. Type-II performance at 23° ....................................................... 5-9
  5.4.3. Type-II performance at 30° ....................................................... 5-10
  5.4.4. Type-II performance estimates at 40° ....................................... 5-11
Chapter 6: Conclusions And Recommendations For Future Work

6.1 INTRODUCTION ................................................................. 6-1
6.2 LEO UHF CHANNEL MEASUREMENTS AND CHARACTERISATION .............................................. 6-2
6.2.1. Method of Measurement ......................................................... 6-2
6.2.2. Error statistics of the LEO UHF satellite channel ................... 6-2
6.2.3. The Fritchman model .............................................................. 6-3
6.2.4. The four-state Markov model ................................................ 6-4
6.3 PROTOCOL PERFORMANCE .................................................. 6-4
6.4 ERROR CONTROL TECHNIQUES .............................................. 6-5
6.4.1. A satellite pass at 15° .......................................................... 6-5
6.4.2. For satellite passes at 23°, 30° and 40° ................................. 6-5
6.4.3. A satellite pass experiencing interference at 52° ................... 6-6
6.4.4. A satellite pass at 63° .......................................................... 6-6
6.4.5. A satellite pass at 68° .......................................................... 6-6
6.4.6. A satellite pass from 74° and above ...................................... 6-7
6.4.7. Final Remarks ................................................................. 6-7
6.5 FUTURE WORK IN CHANNEL MEASUREMENTS AND ERROR CONTROL TECHNIQUES .............. 6-8
6.5.1. Future LEO Measurement Campaign ...................................... 6-8
6.5.2. Hybrid-ARQ based on convolutional codes ............................ 6-8
6.5.3. Hybrid-ARQ based on Sequential decoding ............................ 6-9
6.5.4. Hybrid-ARQ with Diversity Combining ................................. 6-10
6.5.5. Majority-logic decoding ........................................................ 6-10
6.5.6. Hybrid-ARQ based on Turbo Codes ...................................... 6-11
6.6 IMPLEMENTATION AND IN-ORBIT DEMONSTRATION ................................................................. 6-12
6.7 FINAL REMARKS ............................................................... 6-13
6.8 REFERENCES ................................................................. 6-15
List of Symbols

Chapter 2

\( C/N \)  
Carrier-to-noise ratio

\( C/I \)  
Carrier-to-Interference ratio

\( E_l \)  
Elevation angle (degrees)

\( E \)  
Electric vector

\( f_d \)  
Doppler frequency (Hz)

\( h \)  
height (m)

\( \lambda \)  
wavelength (m)

\( R \)  
Radius of Earth 6378.1 km

\( \rho_o \)  
Slant path range (m)

\( v \)  
velocity (m/s)

Chapter 3

\( p(r) \)  
probability distribution

\( r \)  
signal envelope

\( \sigma \)  
standard deviation

\( A_c \)  
Line of sight component

\( b_o \)  
average scattered power due to multipath

\( I_0 [\cdot] \)  
modified Bessel function of zeroth order

\( \mu \)  
mean

\( \Delta_o \)  
error density threshold

\( P(0^m/1) \)  
error free run length of at least \( m \) following an error ('1')

\( \chi^2 \)  
Chi-square value

\( f_i \)  
actual frequency of samples

\( \hat{f}_i \)  
expected frequency of samples

\( N_g \)  
Number of gaps

\( N_g(m) \)  
Number of gaps of length \( m \)

\( N_e \)  
Total number of errors

\( P_g(m) \)  
Gap distribution

\( P_{ij} \)  
Transition probability from state \( i \) to \( j \)

Chapter 4

\( d_{\text{min}} \)  
minimum distance of a code

\( e \)  
Erasures

\( R \)  
Code rate

\( t \)  
error-correction capability (symbols)

\( \text{GF}(q) \)  
Galois Field defined over \( q \)

Chapter 5

\( q \)  
\( q \)-ary symbol

\( n \)  
length of the code after encoding

\( k \)  
information length
List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-1</td>
<td>Daily access time versus latitude for 800km polar orbit</td>
<td>2-2</td>
</tr>
<tr>
<td>2-2</td>
<td>Relative path losses for various satellite orbits</td>
<td>2-4</td>
</tr>
<tr>
<td>2-3</td>
<td>VHF/UHF antenna patterns</td>
<td>2-5</td>
</tr>
<tr>
<td>2-4</td>
<td>Exploded view of the modular microsatellites</td>
<td>2-9</td>
</tr>
<tr>
<td>2-5</td>
<td>Microsatellite with boom deployed</td>
<td>2-10</td>
</tr>
<tr>
<td>2-6</td>
<td>The Terrestrial network</td>
<td>3-3</td>
</tr>
<tr>
<td>3-3</td>
<td>Propagation model for mobile satellite channels</td>
<td>3-4</td>
</tr>
<tr>
<td>3-4</td>
<td>Block diagram of transmitter</td>
<td>3-7</td>
</tr>
<tr>
<td>3-5</td>
<td>Block diagram of receiver</td>
<td>3-7</td>
</tr>
<tr>
<td>3-6</td>
<td>Block diagram of ground station</td>
<td>3-8</td>
</tr>
<tr>
<td>3-7</td>
<td>SSTL Operations and Mission Control groundstation</td>
<td>3-9</td>
</tr>
<tr>
<td>3-8</td>
<td>Schematic of scrambler</td>
<td>3-9</td>
</tr>
<tr>
<td>3-9</td>
<td>Schematic of de-scrambler</td>
<td>3-10</td>
</tr>
<tr>
<td>3-10</td>
<td>UOSAT-3 UHF antenna pattern</td>
<td>3-21</td>
</tr>
<tr>
<td>3-11</td>
<td>Gilbert's model and transition matrix</td>
<td>3-23</td>
</tr>
<tr>
<td>3-12</td>
<td>Fritchman's partitioned Markov chain and matrix of transition probabilities</td>
<td>3-26</td>
</tr>
<tr>
<td>3-13</td>
<td>Fritchman's state diagram and matrix of transition probabilities for a 23° satellite pass</td>
<td>3-30</td>
</tr>
<tr>
<td>3-14</td>
<td>Fritchman's state diagram and matrix of transition probabilities for a 30° satellite pass</td>
<td>3-30</td>
</tr>
<tr>
<td>3-15</td>
<td>A UHF digital error sequence simulator</td>
<td>3-33</td>
</tr>
<tr>
<td>3-16</td>
<td>A four-state probabilistic Markov model</td>
<td>3-38</td>
</tr>
<tr>
<td>4-1</td>
<td>PACSAT protocol hierarchy</td>
<td>4-3</td>
</tr>
<tr>
<td>4-2</td>
<td>PACSAT broadcast hole-filling</td>
<td>4-4</td>
</tr>
<tr>
<td>4-3</td>
<td>PBP server diagram in bytes (not to scale)</td>
<td>4-4</td>
</tr>
<tr>
<td>4-4</td>
<td>PBP client datagram format in bytes (not to scale)</td>
<td>4-4</td>
</tr>
<tr>
<td>4-5</td>
<td>AX25 frame structure in bytes (not to scale)</td>
<td>4-5</td>
</tr>
<tr>
<td>4-6</td>
<td>Reed-Solomon code decomposition for the type-II protocol</td>
<td>4-11</td>
</tr>
<tr>
<td>4-7</td>
<td>Flow chart of the type-II hybrid operation</td>
<td>4-12</td>
</tr>
<tr>
<td>4-8</td>
<td>Block interleaving process</td>
<td>4-13</td>
</tr>
<tr>
<td>4-9</td>
<td>OPNET tools and modelling structure</td>
<td>4-15</td>
</tr>
<tr>
<td>4-10</td>
<td>Layered protocol architecture</td>
<td>4-16</td>
</tr>
<tr>
<td>4-11</td>
<td>Stages in the communications link</td>
<td>4-16</td>
</tr>
<tr>
<td>4-12</td>
<td>Example of an FSM in OPNET</td>
<td>4-17</td>
</tr>
<tr>
<td>4-13</td>
<td>Finite State Machine and Events in the sliding window protocol</td>
<td>4-19</td>
</tr>
<tr>
<td>6-1</td>
<td>Satellite and Ground Station AX.25 Servers</td>
<td>6-12</td>
</tr>
</tbody>
</table>
## List of Graphs

| Graph 3-1a | Burst histogram at 15° | 3-12 |
| Graph 3-1b | Burst histogram at 20° | 3-12 |
| Graph 3-1c | Burst histogram at 30° | 3-12 |
| Graph 3-1d | Burst histogram at 40° | 3-12 |
| Graph 3-1e | Burst histogram at 52° | 3-13 |
| Graph 3-1f | Burst histogram at 63° | 3-13 |
| Graph 3-1g | Burst histogram at 74° | 3-13 |
| Graph 3-1h | Burst histogram at 80° | 3-13 |
| Graph 3-1i | Burst histogram comparisons from 15° to 40° | 3-14 |
| Graph 3-1j | Burst histogram comparisons from 52° to 74° | 3-14 |
| Graph 3-2a | Gap histogram at 15° | 3-15 |
| Graph 3-2b | Gap histogram at 20° | 3-15 |
| Graph 3-2c | Gap histogram at 30° | 3-15 |
| Graph 3-2d | Gap histogram at 40° | 3-15 |
| Graph 3-2e | Gap histogram at 52° | 3-16 |
| Graph 3-2f | Gap histogram at 63° | 3-16 |
| Graph 3-2g | Gap histogram at 74° | 3-16 |
| Graph 3-2h | Gap histogram at 80° | 3-16 |
| Graph 3-2i | Gap histogram comparisons from 15° to 40° | 3-17 |
| Graph 3-2j | Gap histogram comparisons from 52° to 74° | 3-17 |
| Graph 3-3a | Histogram of bursts for a 15° Pass | 3-18 |
| Graph 3-3b | Histogram of gaps for a 15° Pass | 3-18 |
| Graph 3-4a | Histogram of bursts for a 23° Pass | 3-19 |
| Graph 3-4b | Histogram of gaps for a 23° Pass | 3-19 |
| Graph 3-5a | Histogram of bursts for a 40° Pass | 3-19 |
| Graph 3-5b | Histogram of gaps for a 40° Pass | 3-19 |
| Graph 3-6a | Histogram of bursts for a 52° Pass | 3-19 |
| Graph 3-6b | Histogram of gaps for a 52° Pass | 3-19 |
| Graph 3-7a | Histogram of bursts for a 80° Pass | 3-20 |
| Graph 3-7b | Histogram of gaps for a 80° Pass | 3-20 |
| Graph 3-8 | Cumulative histogram of burst lengths from 15° to 74° | 3-20 |
| Graph 3-9 | Cumulative histogram of gap lengths from 15° to 74° | 3-20 |
| Graph 3-10a | Clustering of bursts for a satellite pass at 80° | 3-22 |
| Graph 3-10b | Corresponding gap lengths distribution for 80° | 3-22 |
| Graph 3-11 | Histogram of bursts and exponential curve approximations at 23° | 3-24 |
| Graph 3-12 | Histogram of bursts and exponential curve approximations at 40° | 3-24 |
Graph 3-13: Histogram of gaps and exponential curve approximations at 23°................. 3-25
Graph 3-14: Histogram of gaps and exponential curve approximations at 52°................. 3-25
Graph 3-14: Gap-between-errors distribution for a 23° elevation pass.......................... 3-27
Graph 3-16a: Experimental interval length distribution and Fritchman's model for a 23° satellite pass .... 3-29
Graph 3-16b: Experimental interval length distribution and Fritchman's model for a 30° satellite pass........ 3-29
Graph 3-16c: Experimental interval length distribution and Fritchman's model for a 40° satellite pass........ 3-29
Graph 3-16d: Experimental interval length distribution and Fritchman's model for a 52° satellite pass........ 3-29
Graph 3-16e: Experimental interval length distribution and Fritchman's model for a 62° satellite pass........ 3-29
Graph 3-16f: Experimental interval length distribution and Fritchman's model for a 74° satellite pass........ 3-29
Graph 3-17a: Experimental burst interval for a satellite pass at maximum elevation 62°.............. 3-31
Graph 3-17b: Experimental burst interval for a satellite pass at maximum elevation 74°.............. 3-31
Graph 3-18a: Experimental and generated interval lengths distribution for a 23° satellite pass........ 3-33
Graph 3-18b: Experimental and generated interval lengths distribution for a 30° satellite pass........ 3-33
Graph 3-18c: Experimental and generated interval lengths distribution for a 40° satellite pass........ 3-34
Graph 3-18d: Experimental and generated interval lengths distribution for a 52° satellite pass........ 3-34
Graph 3-18e: Experimental and generated interval lengths distribution for a 63° satellite pass........ 3-34
Graph 3-18f: Experimental and generated interval lengths distribution for a 74° satellite pass........ 3-34
Graph 3-19a: Burst cumulative histogram for a 23° pass........................................... 3-35
Graph 3-19b: Burst cumulative histogram for a 30° pass........................................... 3-35
Graph 3-19c: Burst cumulative histogram for a 40° pass........................................... 3-35
Graph 3-19d: Burst cumulative histogram for a 52° pass........................................... 3-35
Graph 3-19e: Burst cumulative histogram for a 63° pass........................................... 3-35
Graph 3-19f: Burst cumulative histogram for a 68° pass........................................... 3-35
Graph 3-20a: Gap cumulative histogram for a 23° pass............................................ 3-36
Graph 3-20b: Gap cumulative histogram for a 30° pass............................................ 3-36
Graph 3-20c: Gap cumulative histogram for a 40° pass............................................ 3-36
Graph 3-20d: Gap cumulative histogram for a 52° pass............................................ 3-36
Graph 3-20e: Gap cumulative histogram for a 63° pass............................................ 3-36
Graph 3-20f: Gap cumulative histogram for a 68° pass............................................ 3-36
Graph 3-21a: Burst cumulative histogram for a 23° pass........................................... 3-41
Graph 3-21b: Burst cumulative histogram for a 30° pass........................................... 3-41
Graph 3-21c: Burst cumulative histogram for a 40° pass........................................... 3-41
Graph 3-21d: Burst cumulative histogram for a 52° pass........................................... 3-41
Graph 3-21e: Burst cumulative histogram for a 62° pass........................................... 3-41
Graph 3-21f: Burst cumulative histogram for a 74° pass........................................... 3-41
Graph 3-22a: Gap cumulative histogram for a 23° pass............................................ 3-42
Graph 3-22b: Gap cumulative histogram for a 30° pass............................................ 3-42
Graph 3-22c: Gap cumulative histogram for a 40° pass............................................ 3-42
Graph 3-22d: Gap cumulative histogram for a 52° pass............................................ 3-42
Graph 3-22e: Gap cumulative histogram for a 62° pass ................................................................................... 3-42
Graph 3-22f: Gap cumulative histogram for a 74° pass ................................................................................... 3-42
Graph 5-1: Experimental vs generated data from 4-state and Fritchman model for a 15° pass ......................... 5-4
Graph 5-2: Experimental vs generated data from 4-state and Fritchman model for a 23° pass ......................... 5-4
Graph 5-3: Experimental vs generated data from 4-state and Fritchman model for a 30° pass ......................... 5-4
Graph 5-4: Experimental vs generated data from 4-state and Fritchman model for a 40° pass ......................... 5-4
Graph 5-5: Experimental vs generated data from 4-state and Fritchman model for a 52° pass ......................... 5-4
Graph 5-6: Experimental vs generated data from 4-state and Fritchman model for a 63° pass ......................... 5-4
Graph 5-7: Experimental vs generated data from 4-state and Fritchman model for a 68° pass ......................... 5-5
Graph 5-8: Experimental vs generated data from 4-state and Fritchman model for a 74° pass ......................... 5-5
Graph 5-9: % decodable packets vs coding rate for the type-II hybrid for a range of elevation angles .......... 5-26
Graph 5-10: Performance of byte (64,k) byte interleaving for a satellite pass at 15° ....................................... 5-27
Graph 5-11: Performance of byte (64,k) byte interleaving for a satellite pass at 23° ....................................... 5-28
Graph 5-12: Performance of byte (64,k) byte interleaving for a satellite pass at 30° ....................................... 5-29
Graph 5-13: Performance of byte (64,k) byte interleaving for a satellite pass at 40° ....................................... 5-29
Graph 5-14: Performance of byte (64,k) byte interleaving for a satellite pass at 52° ....................................... 5-30
Graph 5-15: Performance of byte (64,k) byte interleaving for a satellite pass at 63° ....................................... 5-31
Graph 5-16: Performance of byte (64,k) byte interleaving for a satellite pass at 68° ....................................... 5-31
Graph 5-17: Performance of byte (64,k) byte interleaving for a satellite pass at 74° ....................................... 5-32
Graph 5-18: Performance of byte (128,k) byte interleaving for a satellite pass at 15° ....................................... 5-33
Graph 5-19: Performance of byte (128,k) byte interleaving for a satellite pass at 23° ....................................... 5-34
Graph 5-20: Performance of byte (128,k) byte interleaving for a satellite pass at 30° ....................................... 5-35
Graph 5-21: Performance of byte (128,k) byte interleaving for a satellite pass at 40° ....................................... 5-35
Graph 5-22: Performance of byte (128,k) byte interleaving for a satellite pass at 52° ....................................... 5-36
Graph 5-23: Performance of byte (128,k) byte interleaving for a satellite pass at 63° ....................................... 5-37
Graph 5-24: Performance of byte (128,k) byte interleaving for a satellite pass at 68° ....................................... 5-37
Graph 5-25: Performance of byte (128,k) byte interleaving for a satellite pass at 74° ....................................... 5-38
List of Tables

Table 1-1: Summary of LEO constellations .................................................................................................................. 1-2
Table 2-1: Groundstation and satellite antennas ...................................................................................................... 2-4
Table 3-1: Channel models representing different environments .................................................................................. 3-5
Table 3-2: Orbital characteristics of UOSAT-3 .......................................................................................................... 3-7
Table 3-3: Average Bit Error Rate for a range of satellite elevation angles ................................................................. 3-18
Table 3-4: Link budget analysis for UOSAT-3 ............................................................................................................ 3-21
Table 3-5: Several proposed generative models ......................................................................................................... 3-22
Table 3-6: Chi-square comparison of the error sequences .......................................................................................... 3-24
Table 3-7: Coefficients through curve-fitting procedure for a range of elevation angles ........................................... 3-31
Table 3-8: Fritchman model transition probabilities for a range of elevation angles ................................................ 3-31
Table 3-9: Transition probabilities for the 4-state model for a range of elevation angles ........................................... 3-40
Table 3-10: Comparison of statistics between the experimental data and 4-state model for a range of elevation angles ................................................................................................................................................ 3-40
Table 5-1: Results of (128,k) punctured code for a 15° satellite pass ....................................................................... 5-8
Table 5-2: Results of (128,k) punctured code for a 23° satellite pass ....................................................................... 5-9
Table 5-3: Results of (128,k) punctured code for a 30° satellite pass ....................................................................... 5-10
Table 5-4: Results of (128,k) punctured code for a 40° satellite pass ....................................................................... 5-11
Table 5-5: Results of (128,k) punctured code for a 52° satellite pass ....................................................................... 5-12
Table 5-6: Results of (128,k) punctured code for a 63° satellite pass ....................................................................... 5-13
Table 5-7: Results of (128,k) punctured code for a 68° satellite pass ....................................................................... 5-14
Table 5-8: Results of (128,k) punctured code for a 74° satellite pass ....................................................................... 5-15
Table 5-9: Performance of ARQ-only system and achievable throughput of the type-II protocol ............................ 5-16
Table 5-10: The number of packets that pass or fail the mothercode operation with variable delays and buffer size of 16 packets for the experimental data at 15° .................................................................................... 5-18
Table 5-11: The number of packets that pass or fail the mothercode operation with variable delays and buffer size of 16 packets for the Fritchman model at 15° .................................................................................... 5-18
Table 5-12: The percentage of packets recovered with the mothercode with variable delays and buffer size of 16 packets for the experimental data at 52° .................................................................................... 5-20
Table 5-13: The number of packet timeouts and discards for buffer sizes of 8 and 16 and delay parameter of 6 packets ......................................................................................................................................... 5-20
Table 5-14: The number of packets recovered with the mothercode with variable delays and buffer size of 16 packets for the Fritchman model at 52° .................................................................................... 5-21
Table 5-15: The percentage of packets recovered with the mothercode for variable delays and buffer size of 16 packets for the experimental data at 68° .................................................................................... 5-22
Table 5-16: The percentage of packets recovered with the mothercode for variable delays and buffer size of 16 packets for the Fritchman model at 68° .................................................................................... 5-22
Table 5-17: The number of packet timeouts for various buffer sizes and delay parameters for the experimental data at 74° .................................................................................................................................... 5-23
Table 5-18: The number of packet timeouts for various buffer sizes and delay parameters for the 4-state model at 74° .................................................................................................................................... 5-23
Table 5-19: The percentage of packets successfully decoded with the mothercode for a buffer size of 32 packets and various delay parameters for the experimental data at 74°  5-24
Table 5-20: Total throughput of the SR-ARQ PB protocol for a range of elevation angles  5-24
Table 5-21: Performance of the type-II hybrid for a satellite pass from 15° to 23°  5-24
Table 5-22: Performance of the type-II hybrid for a satellite pass from 15° to 30°  5-25
Table 5-23: Performance of the type-II hybrid for a satellite pass from 15° to 40°  5-25
Table 5-24: Performance of the type-II hybrid for a satellite pass from 15° to 52°  5-25
Table 5-25: Performance of the type-II hybrid for a satellite pass from 15° to 63°  5-26
Table 5-26: Performance of the type-II hybrid for a satellite pass from 15° to 68°  5-26
Table 5-27: (64,k) byte interleaving for a 15° satellite pass  5-27
Table 5-28: (64,k) byte interleaving for a 23° satellite pass  5-28
Table 5-29: (64,k) byte interleaving for a 30° satellite pass  5-29
Table 5-30: (64,k) byte interleaving for a 40° satellite pass  5-29
Table 5-31: (64,k) byte interleaving for a 52° satellite pass  5-30
Table 5-32: (64,k) byte interleaving for a 63° satellite pass  5-31
Table 5-33: (64,k) byte interleaving for a 68° satellite pass  5-32
Table 5-34: (64,k) byte interleaving for a 74° satellite pass  5-32
Table 5-35: (128,k) byte interleaving for a 15° pass  5-33
Table 5-36: (128,k) byte interleaving for a 23° pass  5-34
Table 5-37: (128,k) byte interleaving for a 30° pass  5-35
Table 5-38: (128,k) byte interleaving for a 40° pass  5-35
Table 5-39: (128,k) byte interleaving for a 52° pass  5-36
Table 5-40: (128,k) byte interleaving for a 63° pass  5-37
Table 5-41: (128,k) byte interleaving for a 68° pass  5-38
Table 5-42: (128,k) byte interleaving for a 74° pass  5-38
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Chapter 1

Low Earth Orbit Satellite Communications

1.1. INTRODUCTION ................................................................. 1
1.2. OBJECTIVES AND SCOPE OF THE RESEARCH ............... 3
1.3. STRUCTURE OF THIS THESIS ........................................ 4
1.4. REFERENCES ....................................................................... 5

1.1. Introduction

Low-Earth Orbit (LEO) satellites have made access to space-based services possible for a large number of users around the globe with a wide range of applications, from space science research, environmental monitoring, tactical military applications and technology testbeds to communications to serve both military and civilians. With the emergence of cellular radio technology, there has been a renewal of interest in low-earth-orbiting satellite communication networks.

In particular, small satellites in LEO have gained a competitive edge in the communications satellite market, upon widespread realisation of their significant advantages over the conventional satellites - lower costs, smaller path losses and reduced propagation delays while able to accommodate state-of-the-art technologies.

In 1945, British scientist and author Arthur C. Clarke answered a momentous question: is it possible for rocket stations to provide worldwide radio coverage? [Clarke45] The answer to his query came in the form of geostationary satellite communications and subsequently, a revolution in global telecommunications. The development of numerous LEO satellite constellations, containing dozens, even hundreds, of spacecraft is taking place as this thesis is completed. A new generation of Global Mobile Personal Communications Services (GMPCS) which primarily consist of LEO satellites are proposing ubiquitous telecommunications worldwide by using hand-held portable terminals. Among the major players in the race to LEO that concentrate mainly on voice-based services include Iridium, Globalstar, and ICO Global while other systems that predominantly provide data-based services include Orbcomm. Several such systems are summarised in Table 1-1 as follows.
<table>
<thead>
<tr>
<th>No</th>
<th>SYSTEM</th>
<th>ORBIT</th>
<th>INCLIN. HEIGHT</th>
<th>FREQUENCY (MHz)</th>
<th>MULTIPLE ACCESS, CODES AND SERVICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LEOSAT</td>
<td>18 satellites 2 planes/6</td>
<td>40°, 970 km</td>
<td>148-149, 137-138</td>
<td>Data 4.8kbps</td>
</tr>
<tr>
<td>2</td>
<td>Orbcomm</td>
<td>20 satellites 2 in polar 18 inclined</td>
<td>90°, 40-60° 970 km</td>
<td>148-149.9</td>
<td>FDMA dynamic SS PSK burst pkt comms Data: 50kbps feeder 2 4 kup/4.8k down</td>
</tr>
<tr>
<td>3</td>
<td>StarNet</td>
<td>24 satellites 6 planes/4 satellites</td>
<td>53°, 1300 km</td>
<td>148-149</td>
<td>FDMA w/ DS/CDMA, ½ rate conv. code DS-SS chip rate 1Mbps Data 4.8k up 9.6k down</td>
</tr>
<tr>
<td>4</td>
<td>Vitasat</td>
<td>2 satellites 2 planes /1</td>
<td>98°,800 km</td>
<td>VHF UHF</td>
<td>Data: 2.4k/9.6k</td>
</tr>
<tr>
<td>5</td>
<td>Aries</td>
<td>4 planes /12 satellites</td>
<td>90°,1018 km</td>
<td>1610-1625.5, 6525-5215(d/d)</td>
<td>Data 2.4k Voice 4.8k</td>
</tr>
<tr>
<td>6</td>
<td>Ellipso</td>
<td>24 total satellites 15: 3 planes / 5 9: 1 plane / 9</td>
<td>116°,520 km /7800km 0°,7800 km</td>
<td>1610-1625.5 2483.5-2500</td>
<td>SS/FDMA</td>
</tr>
<tr>
<td>7</td>
<td>Globalstar</td>
<td>48 satellites 8 planes /6 satellites</td>
<td>52° 1387.5 km</td>
<td>L-band user 5G gateway (u/l) S-band user 7G gateway (d/d)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Iridium</td>
<td>66 satellites 6 planes/11 satellites</td>
<td>86.4° 789km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>ICO</td>
<td>12 satellites 10 operational 2 spares, 2 planes 5 satellites/plane</td>
<td>45° 10355 km</td>
<td>S-band</td>
<td>TDMA, path diversity GSM</td>
</tr>
<tr>
<td>10</td>
<td>TermaSat</td>
<td>2 satellites 1 plane/ 2 satellites</td>
<td>82.5° 950 km</td>
<td>148-150.05, 401-403 137-139</td>
<td>SCPC (u/l) TDM Data2 4k/9.6k</td>
</tr>
<tr>
<td>11</td>
<td>Taos</td>
<td>5 satellites 5 planes/1 satellite</td>
<td>57° 1208 km</td>
<td>148-150 137-138,400</td>
<td>return CDMA DS-SS Data 1.2k inbound, 14k outbound</td>
</tr>
<tr>
<td>12</td>
<td>Gonets</td>
<td>36 satellites 6 planes /6 satellites</td>
<td>83°,1400km</td>
<td>VHF/UHF, L-band</td>
<td>312-315,1624.5-1643.4 387-390,1541-1541.9 ALOHA u/l TDM Data 4.8k</td>
</tr>
<tr>
<td>13</td>
<td>Teledesic</td>
<td>288 satellites 12 planes/24 satellites</td>
<td>LEOME 28.6-29.1GHz uplink 18.8-19.3GHz downlink</td>
<td>2Mbps uplink, 64Mbps downlink</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>ECCO</td>
<td>12 satellites 11 + 1 spare</td>
<td>Equator</td>
<td>L-band user, C-band feeder S-band user, Ku-band feeder CDMA</td>
<td></td>
</tr>
</tbody>
</table>

In the realm of the newly planned GMPCS, the little-LEO systems often seem to play second fiddle to their big-LEO counterparts. However, the principal difference between the proposed offerings of little-LEO operators and others is they concentrate on providing non-real-time data services, rather than handling real-time voice traffic. The important niche markets for little-LEOs include remote data communications, digital tracking, environmental monitoring and SCADA (Supervisory Control and Data Acquisition) to provide remote monitoring of isolated facilities like mines and oil refineries. Following the first space launch in 1957, the large geostationary satellites have absorbed the engineering attention and resources and through the years, have evolved to even larger and more power-equipped structures. Due to their size and stifling launch costs, these satellites were only accessible to members of an exclusive club, comprising inter-governmental and large space organisations. Between the mid-sixties and eighties, the role of small satellites had been neglected by space-faring nations in favour of getting the most sophisticated performance from the large satellites. As the United States was committed to manned flights, including lunar missions, large boosters were developed, which were subsequently used to place large payloads into geostationary orbit.

LEO satellites were traditionally used for weather monitoring, resource mapping and Earth exploration. However, after more than three decades of satellite development, a fraction of the energy spent on conventional satellite technology is focusing on relatively small, highly capable and reliable spacecraft.
Chapter 1: Low Earth Orbit Satellite Communications

The change in world politics and military emphasis has brought about a shift to increasing commercialisation of space activities. However, the engineering of low-cost miniature spacecraft differs from that of established space engineering techniques. Among the key technologies driving the satellite revolution, advances in semiconductor memory and microprocessor technology have enabled miniaturisation of the size and capabilities of space components. This has made feasible the development of smaller satellites and ground terminals that are constantly decreasing in size and mass. These shrinking satellite attributes have had great impact upon new space systems: their capabilities, affordability and availability. Yet these systems have to fulfil consumer market requirements to provide services while maintaining the same performance as the large satellites, if not better. Further advances in data compression, optics and payload technology have enabled these small but highly capable spacecraft to accommodate mass quantities of data on-board. This new breed of ‘smaller, cheaper and rapid-response’ satellites as opposed to the large conventional satellites have been spurred by the combination of reduced space budgets and increasing capability of low-power microelectronics. In the very near future, the new LEO satellites are set to provide a wide range of services to the world of communications. It is within this context that this research is undertaken.

1.2. Objectives and Scope of the Research

The primary objective of this research is to characterise the LEO satellite communications channel and study, design and simulate error-control techniques under real dynamic conditions of the channel to achieve optimal throughput performance. The scope of this research covers a wide area which encompasses channel modelling, protocols and error-control coding. In a more detailed context, the aims of this research are to initially conduct a LEO measurement campaign based on an in-orbit LEO satellite and to understand the underlying error mechanisms observed in the channel. It is essential to investigate the channel fading phenomena and to examine the extent of multipath fading, shadowing and interference and influence of varying elevation angle upon the channel. Suitable channel models to characterise the observed fading statistics are investigated. It is the goal of this research to find adequate characterisation parameters for the LEO channel based on a wide range of elevation angles and finally, to develop a model that will function as an adequate channel simulator based on real in-orbit data. Having achieved the aforementioned tasks, the following aim of the research is to examine the performance of hybrid-ARQ and coding techniques based on the existing spacecraft platform. This research endeavours to identify the tradeoffs between different error control strategies, to select the optimal code parameters such as coding rates, having taken into consideration necessary tradeoffs, and measure the amount of achievable throughput performance improvement compared with the current
ARQ-only system. The advantages and disadvantages of each error control technique are discussed and various implementation issues such as buffering considerations are highlighted. The optimal coding scheme for a wide range of channel conditions will be recommended for future implementation purposes and the feasibility of such issues will be dealt with.

For simulation purposes, a proper simulation tool is selected and utilised to simulate the performance of the various error control strategies.

A comprehensive literature survey is carried out that covers a broad range of issues such as background information on the characteristics of the LEO channel and how it differs from the geostationary satellite link, channel modelling techniques, coding and hybrid-ARQ schemes and protocols.

The eventual goal of the research is to implement and demonstrate the feasibility of such hybrid-ARQ schemes or coding techniques that can provide further improvements in performance based in a real-world environment on a LEO satellite in-orbit.

This research was undertaken as a component of the ongoing development of the University of Surrey series of little-LEO microsatellites. Surrey Satellite Technology Limited (SSTL) at the Surrey Space Centre in the University of Surrey has designed, built and launched fourteen microsatellites into LEO and recently, a UoSAT-12 minisatellite launched in April 1999. All of SSTL small satellites operate in store-and-forward mode which directly imply that they offer non-real-time data services. On the other hand, constellations like Iridium, Globalstar and ICO as previously discussed, offer additional real-time voice services. The scope of this research is confined to the point-to-point downlink UHF communications channel between a LEO microsatellite and tracking groundstation located at SSTL's premises, within the grounds of the University of Surrey's campus.

In this context, small satellites will include micro-, mini- and nano-satellites. The results of the research have direct relevance and applicability to all existing and potential users in civilian and military, environmental monitoring, scientific and communications satellites and all future generation of small satellites in LEO.

1.3. Structure Of This Thesis

This thesis consists of six chapters.

This chapter has discussed the emergence of numerous LEO satellite constellations, the issue and the need for optimisation of the LEO satellite communications link, leading to the primary objectives and scope of the research.

Chapter 2 provides a comprehensive background on the research environment, the various factors in and constraints on the performance of a successful communications system in LEO. These factors include the medium of propagation, the adjacent terrain configuration, the satellite orbit, antennae and constraints of the microsatellites. The chapter closes by concluding that deterministic parameters, such as Doppler shifts and path losses, can be easily described by mathematical equations, while effects of
scintillation, multipath fading, shadowing and adjacent interference vary the signal parameters randomly. The characterisation of these unpredictable phenomena are further elaborated in Chapter 3.

Chapter 3 covers a literature survey on the propagation measurements and channel modelling techniques of the LEO satellite channel, mobile-radio terrestrial network and mobile satellite systems. It discusses various types of models utilised to represent each of the channels and makes comparison to the LEO satellite propagation channel. This chapter further describes a measurement campaign that was conducted at the Surrey Space Centre in Guildford and shows that the statistics of the error sequences obtained from such a campaign can be represented by a either a multiple-state Fritchman model or four-state statistical model. The more accurate model of the two for each circumstance is then utilised for simulation purposes for more reliable statistics.

The aspects of layered protocols and the SSTL PACSAT protocol suite system are reviewed in Chapter 4. A literature survey is performed for the protocols used in packet communications to identify state-of-the-art techniques and optimal LEO protocols for payload data retrieval applications. The disadvantages of the current AX.25 link-layer protocol are identified and possible solutions are provided, including error-control techniques. This chapter then discusses the Optimized Network Engineering (OPNET) simulation tool and details the implementation of the SSTL protocols in this tool. The second section of Chapter 4 is dedicated to error-control techniques specifically tailored for a LEO satellite communications channel, and the supporting hardware, including both FEC and hybrid-ARQ schemes. As Reed-Solomon codes were selected, the necessary background theory on these codes are detailed. The advantages and disadvantages of each error-control technique are discussed, adaptive techniques are investigated and potential hybrid-schemes are selected for simulation in the LEO environment. There is further discussion of the results obtained in Chapter 5.

Finally, Chapter 6 presents conclusions and recommends future work that can be carried on to ensure continuity of this research. This final chapter concludes by summarising the main points of each chapter. It states the research novelties, describes the contribution of the research to state-of-the-art space engineering, and discusses the feasibility and expected improvements in throughput performance from hybrid-ARQ techniques in the dynamic and constrained LEO satellite communications channel.

1.4. References

Chapter 2

The Specifics Of Small Satellites In Low Earth Orbit

2.1 INTRODUCTION ................................................................. 1
2.2. THE CHOICE OF ORBIT .......................................................... 2
2.3. THE CHOICE OF FREQUENCY ..................................................... 4
2.4. THE CHOICE OF ANTENNA ...................................................... 4
2.5. RADIOWAVE PROPAGATION EFFECTS ...................................... 5
2.6. THE MICROSATellite STRUCTURE ........................................... 9
2.7. SUMMARY ........................................................................... 11
2.8. REFERENCES ......................................................................... 12

2.1. Introduction

This chapter reviews the many constraints on the design of a successful communication system in a LEO environment. These are categorised into those related to the orbit, impairments from the propagation link, the space environment and the need to implement the systems on a small satellite. Specific to the existing microsatellite platform, the constraints reviewed in this chapter include the design issues related to spacecraft subsystems such as the choice of frequency, orbit, antennas and attitude control. The type of orbit selected and the propagation path determine the specifications of the link. The key propagation mechanisms that alter the characteristics of a signal along the satellite-to-ground propagation path in LEO are identified. The many sources of signal impairments and how they impact upon the system's performance are of crucial importance to any system designer to be able to employ engineering techniques and restore performance. The further complications imposed by the small size of the satellites are reviewed. Each of the above factors has to be taken into consideration and the various solutions require a number of trade-offs between them. The following facts are based on past experience in operating the fleet of SSTL microsatellites for at least eighty in-orbit years in LEO.
2.2. The Choice of Orbit

LEO satellites fall between the range 500km to 2000km in altitude from the surface of the earth, bounded by the outer atmospheric drag and the start of the inner Van Allen radiation belt. Due to the nature of the orbit, the satellite does not appear quasi-stationary as does the GEO satellite.

A single satellite in a highly-inclined LEO can provide global coverage to groundstations anywhere in the world due to the Earth’s rotation and the satellite’s orbital motion. During each orbit, the footprint sweeps a coverage area of approximately 6000 km in diameter, assuming a 700km satellite altitude. A drawback of the UoSAT store-and-forward satellite in LEO is delays in message deliveries. However, for applications that do not depend on instantaneous service delivery, the LEO satellite can ensure provision of service to a global network of users. As the satellite is in a lower orbit, time delays and free space losses are less but instantaneous coverage is also reduced. A further consequence of the satellite passing over the ground station is the propagation conditions can vary greatly at different elevation angles as the path through the atmosphere changes.

For a LEO satellite transit, the parameters are time-varying, dependent upon the frequency of operation and the orbit. Due to the relative movement of the satellites, variations in Doppler shift are experienced. Variations in Doppler shift indicate that the system must compensate for it while variations in path losses imply unequal distribution of link margin which should be utilised most efficiently during the satellite pass. Furthermore, this Doppler compensation and allocation of power margins must be performed within a time-constrained communications window.

2.2.1. Communication Statistics

A typical pass for a LEO satellite lasts for 10 to 15 minutes and messages must be sent and received during this limited communication window. The most crucial statistic shown is that the satellite spends a large proportion of its time at lower elevation angles due to the larger slant path lengths. Studies on a
PoSAT-1 800km sun-synchronous orbit have shown that only 22% of the available communication
time is spent at elevation angles greater than 20 degrees. The rest of the time is spent in the lower
elevation angles where the effects of multipath propagation are more likely to occur. The total access
time in a day as a function of elevation angle is illustrated in Figure 2-1.

2.2.2. Doppler Shift

Doppler shift occurs when there is relative velocity between the observer and the observed object. In
the LEO satellite scenario, the receiving ground terminal is mainly stationary, therefore, the Doppler
shift contributed by the velocity of the ground terminal is negligible. The Doppler shift formula is
given by:

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

(2-1)

where \( f_d \) is the Doppler frequency, \( v \) is the relative velocity between the transmitter and receiver and \( \lambda \)
is the wavelength. Plots of Doppler curves indicate a maximal positive Doppler shift initially at signal
acquisition, which reduces to zero at time of closest approach, and is maximal negative at loss of
signal. At the time of closest approach, when the satellite is at its maximum elevation, the rate of
change of Doppler shift is highest.

The rate of change in frequency determines how quickly Doppler shift compensation must function and
must be compensated for at the groundstation. Calculations for a 800km LEO satellite altitude give the
maximum Doppler shift as approximately ±3.3kHz at VHF, with a maximum Doppler shift rate of
30Hz/sec at a frequency of 435MHz corresponding to a pass with maximum elevation of 90 degrees. At
UHF, the maximum Doppler shift is ±9.5kHz.

2.2.3. Variations in Free Space Loss

Path loss is a function of frequency; the higher the frequency, the larger the path losses. At UHF, the
free space losses are 142.54dB for a satellite at 800km altitude and 146.76dB at 1300km. Free space
loss is a definition predicated on the use of an isotropic transmitting antenna. When the satellite
appears over the horizon at zero degrees elevation angle and traverses gradually to the maximum
elevation angle corresponding to its orbit, the slant path range varies as well. The slant path range is a
function of elevation angle and is given by the following equation:

\[ \rho_0 = \sqrt{(R + h)^2 - R^2 \cos^2 (EI) - R \sin(EI)} \]  

(2-2)

where the slant range \( \rho_0 \) is a function of elevation angle \( (EI) \) for a satellite at height \( h \) above the earth,
and \( R \) is the local radius of the earth at the groundstation.

The maximum slant range is 3293km for a 800km satellite orbit overhead. Hence, the corresponding
one-way transmission delay varies from 2.7ms overhead to 11ms at the horizon.
For an overhead pass of a satellite in an 800km circular orbit, the free space loss varies by over 12dB, while the maximum variation of free space loss for a satellite at 1300km is greater than 10dB. Figure 2-2 illustrates the difference in path loss (dB) experienced when the satellite is at the horizon and zenith which corresponds to zero and ninety degrees elevation angle respectively.

Figure 2-2: Relative Path losses for various satellite orbits

Varying path losses indicate in either case, the system must operate in an efficient manner.

2.3. The Choice of Frequency

The frequencies on the UoSAT microsatellites have been selected as a result of trading off a large number of factors. The spacecraft up- and downlink use the VHF 148-150MHz and UHF 400.15-401MHz frequency bands that are allocated to the ‘little-LEOs’ in the WARC-92. The lower frequency band is preferable for the small, inexpensive microsatellites due to the increase in system complexity, cost, path losses and atmospheric losses at the higher frequencies.

2.4. The Choice of Antenna

The gain of an antenna is a function of its diameter (for dishes), efficiency and the frequency of operation. The SSTL ground station tracking antenna is able to monitor around six to seven passes per satellite in one day. Table 2-1 summarises the different antennas currently incorporated on the satellites and groundstation.

Table 2-1: Groundstation and satellite antennas

<table>
<thead>
<tr>
<th>FREQUENCY</th>
<th>GROUND STATION ANTENNA</th>
<th>SATELLITE ANTENNA</th>
</tr>
</thead>
<tbody>
<tr>
<td>VHF</td>
<td>10 element yagi, CP, 12 dBi</td>
<td>TTC, diplexed λ/4 LP S+F, turnstile, LHCP</td>
</tr>
<tr>
<td>UHF</td>
<td>19/20 turn helix, 16 dBi</td>
<td>TTC, diplexed λ/4 LP S+F, ¼ QFH LHCP</td>
</tr>
<tr>
<td>L-band</td>
<td></td>
<td>S+F, ¼ QFH LHCP</td>
</tr>
<tr>
<td>S-band</td>
<td>2m dish</td>
<td>S+F Tx0 QFH LHCP S+F Tx1 QFH RHCP</td>
</tr>
</tbody>
</table>

By considering the communication statistics and free space loss variations, antenna profiling can provide an improvement in system efficiency. Although the same improvement could be achieved by adjusting the effective isotropic radiated power or data rate control, antenna profiling can be applied to both the up- and downlink. It also simplifies the requirements for the groundstation antenna, which must provide equal gain for all elevation angles.

![Figure 2-3: VHF/UHF Antenna Patterns](image)

The ground station and satellite antennas can be designed to compensate for the link variation due to varying path loss, to provide a uniform link budget at all elevations. This in effect cancels the 12dB variation between zenith and horizon. Therefore, the on-board antenna system is shaped closely to match the inverse function of the free space losses and gives a constant margin. Such an antenna pattern essentially has a gain gradually decreasing from 12dB to 0dB as the elevation increases from zero to ninety degrees.

The ground-tracking antennas are steered in azimuth and elevation. As these antennas are tracking antennas, the overall performance of a system increases, compared to an omni-directional antenna of small ground terminals. Yet these systems with high-gain directive antennas are subject to multipath propagation for very low elevation angles between five and ten degrees. In comparison, a quadrifilar helix antenna of hemispherical radiation of 3dB gain is normally employed for the ground terminals and they do not compensate for the variations in path loss.

### 2.5. Radiowave Propagation Effects

The six principal link-related impairment phenomena that contribute to an overall degradation of the LEO communications link are ionospheric effects, tropospheric scintillation effects, attenuation, depolarisation, multipath fading and interference. The choice of operating frequency is a critical factor in determining whether impairments to the link will be introduced by the Earth’s atmosphere. At the lower frequency region (<3GHz), the predominant effects are scintillation and Faraday rotation produced by the ionosphere. At the higher frequency region (>3GHz) the effects are determined mainly
Chapter 2: The specifics of satellites in low Earth orbit

by the troposphere and include tropospheric scintillation, gaseous and hydrometeor attenuation and depolarisation [Ippolito86]. Multipath fading and interference are dependent upon the adjacent terrain configuration and existence of any potential interferers. Therefore, the geographical position of the groundstation determines the severity of these effects.

2.5.1. Ionospheric Scintillation

Ionospheric scintillation occurs between 200 and 400km in altitude in the ionospheric F region and is most prevalent through the equatorial, auroral and polar regions, and during high-activity sunspots. Ionospheric scintillation is often the limiting factor for reliable communications in the VHF (30-300MHz) band [CCIR 263-4]. Values exceeding 10dB peak-to-peak amplitude fluctuations for equatorial, auroral and sub-auroral latitudes have been recorded previously [Crane77]. For most cases, the impact of ionospheric amplitude scintillations will not be system limiting on an annual average basis but for GEO earth stations close to the equator, the worst month criteria can not be met at periods of high sunspot activity. Severe peak-to-peak amplitude fluctuations cause angle-of-arrival impairments such as depointing of the antenna. This phenomenon occurs for large aperture antennas of 10m or more and at frequencies above 10GHz and can be compensated for through proper tracking systems.

The observable effects of scintillation upon the system are a relatively constant degradation similar to Additive White Gaussian Noise (AWGN) due to the small variations in the signal amplitude. In addition to AWGN, there exist peak-to-peak fluctuations which give rise to bursts and the burst period for the extreme case is usually less than 30 seconds. [Allnutt89] The only effective way to overcome impairments of ionospheric amplitude scintillation is through a Forward Error Correction (FEC) code to counteract the AWGN component and FEC and interleaving techniques to handle the periodic bursts.

2.5.2. The Faraday Effect

For circularly polarised signals, Faraday rotation is not significant and is largely undetectable in most systems. However, this phenomenon is critical on linearly-polarised VHF links. The Faraday effect occurs when the radiowave interacts with the electrons in the ionosphere in the presence of the earth's magnetic field and produces a polarisation rotation. At 4GHz, the maximum variation in rotation is 10 degrees corresponding to a 0.1dB signal loss for linearly polarised systems. The polarisation angle can change with elevation angle by up to 30 degrees for a LEO 800 km orbit.
2.5.3. Tropospheric Scintillation

Tropospheric scintillation effects increase with frequency (>3GHz) and with decreasing elevation angle. Tropospheric scintillation can occur up to 20km in altitude from the earth’s surface and vary according to the seasons, from day to day and with local climate.

Tropospheric scintillation effects gradually decrease at very low elevation angles (around 1°) when multipath effects begin to dominate. Between the range of 10° to 1°, there is a gradual shift in the importance of tropospheric scintillation effects to purely multipath effects. The effects from tropospheric scintillation are similar to the shallow fades in ionospheric scintillation and can be considered as AWGN. Therefore, an FEC code will be sufficient to reduce such impairments.

2.5.4. Gaseous and Hydrometeor Attenuation

Gaseous attenuation is negligible at frequencies lower than 10GHz and does not exceed 1 to 2 dB at 22GHz. Gaseous attenuation is an absorption process (reduction in the amplitude of a radiowave) caused by the presence of atmospheric gases, primarily oxygen and water vapour. When the energy of the radiowave from oscillating charged particles collides with heavy neutral atoms, the energy is said to be ‘absorbed’ and is radiated as thermal energy.

Hydrometeor (rain, clouds, fog, snow, ice) attenuation involves both absorption and scattering processes. A radiowave is scattered when its energy is redirected, without loss of energy to the scattering particle. Rain attenuation can produce major impairments at frequencies above 10GHz. Cloud and fog attenuation is much less severe but must be considered for frequencies above 15GHz, while the effects of dry snow and ice attenuation is observable at links operating above 30GHz. [Ippolito86] The effects of attenuation cause an increase in noise temperature and therefore, a reduction in signal-to-noise (C/N) ratio.

2.5.5. Multipath Fading

Multipath fading is predominant for terrestrial and mobile satellite links, especially at low elevation angles where there exist numerous obstructions and there is less likelihood of line-of-sight occurring. The non-uniformity of terrain, surface roughness and the presence of scatterers (buildings, trees, hills, etc.) along the propagation channel cause the signal to arrive at the receiver via many paths. In the literature, the fading phenomena are well documented and these issues are reviewed [Chapter3].

Multipath fading not only increases the peak-to-peak signal amplitude fluctuations as the elevation angle decreases, but also causes a drop in the mean signal level. The shallow fades in the signal can be treated as AWGN, while deep fades produce bursts that are much longer than most interleaved or concatenated codes can handle. Increasing the transmitted power is one solution, has only limited value as multipath signals can add destructively at the receiver. Techniques normally employed include...
frequency diversity, height/space diversity, orbital diversity, polarisation shaping of the antennas and beam-shaped antennas.

2.5.6. Depolarisation

Depolarisation is a change in the polarisation sense of the transmitted radiowave and is induced either from multipath propagation or hydrometeors. Rain-induced depolarisation occurs because the raindrops are not perfectly spherical, rather they are oblate spheroids and have the tendency for a preferred alignment. The radiowave propagation through such a medium experiences differential attenuation and differential phase shift, which in effect causes a tilt in the resultant electric vector, $E_{\text{out}}$ with respect to incident vector $E_{\text{in}}$. If $E_{\text{out}}$ is resolved into the original axes of $E_{\text{in}}$, it is made up a co-polarised vector parallel to $E_{\text{in}}$ and an orthogonal (cross-polarised) vector to $E_{\text{in}}$. The energy in the wanted sense of polarisation is that of the co-polarised component while the cross-polarised component is undesirable. Ice depolarisation occurs when ice particles are not randomly oriented but have a preferred alignment. The major axes of these ice particles can be abruptly aligned by an event such as a lightning discharge. Rain and ice depolarisation can be problematic above 12GHz, in particular for frequency reuse links which employ dual independent orthogonal polarised channels for the same frequency band. Unlike path attenuation, depolarisation does not cause any increase in the system noise. Instead, it causes a reduction in signal-to-interference (C/I) ratio. Depolarisation will cause the energy of one polarisation sense to be coupled to the other, therefore causing interference.

Multipath depolarisation is limited to very low elevation angles and is dependent on the polarisation characteristics of the receiving antenna. Polarisers, either fixed or rotated, are normally employed to rectify this problem.

2.5.7. Noise and interference

Radio noise is emitted by both natural and man-made sources will add directly to the system noise through an increase in the antenna temperature, either through the main beam or sidelobes. With proper design of an antenna subsystem, unwanted surface emission due to these sources can be protected against. Between about 30MHz and 1GHz, the prime contributor of noise on the link arise from man-made sources in populated areas. Interference is a particular type of man-made noise and is unpredictable. To limit its impact upon the system, one could employ directive beams with a null at the direction of the noise source, narrower receiver bandwidths, etc.
2.6. **The Microsatellite Structure**

The microsatellites impose further constraints, owing to their limited power, spacecraft size and structure and antenna platforms. The design drivers for the communications system are to provide maximum data throughput for the least required mass, volume and on-board power.

![Exploded view of the modular microsatellites](image)

**Figure 2-4: Exploded view of the modular microsatellites**

2.6.1. **Spacecraft size**

The Ariane Structure for Auxiliary Payload (ASAP) has permitted multiple launch opportunities for microsatellites as secondary payloads. However, the launch structure essentially limits the size of the payloads to a mass of around 50kg and a volume of 330*330*29-35mm, the size of the module tray. These impose restrictions on mass, volume and power. As the microsatellite is size-constrained, the choice of antennas on the satellite is restricted.

2.6.2. **Power Onboard**

Four body-mounted solar panels located in the four sides of the microsatellite generate a maximum power of 35W each from Gallium Arsenide (GaAs) cells of 19.2% efficiency. When deployed, they provide slightly more power. Restricted satellite volume limits the area available for body-mounted solar arrays. Deployable arrays are feasible within some microsatellite budgets, but they inevitably increase mission complexity, cost and risk due to mechanical unreliability. Furthermore, the satellite does not reside in sunlight all the time; there are inevitably regular periods where it is in the Earth’s...
shadow as well. Of the total 18W average orbit power generated, approximately 10W is allocated to the spacecraft bus, and the rest for additional payloads.

2.6.3. Choice of attitude control

The UoSAT microsatellites use passive gravity-gradient torques that keep the satellite Earth-pointing and employs magnetorquers that act against the earth’s magnetic field to produce a torque which tends to rotate the spacecraft. This gravity-gradient / magnetorquer combination is reliable and inexpensive, and achieves a pointing accuracy within 0.5 to 5 degrees of nadir.

As the satellite is spinning, the radio waves cannot be described as vertically or horizontally polarised, as there is no reference plane in the wave. Therefore, the waves will be arbitrarily vertical, horizontal or a combination of both and the polarisation may alter between orbits. An additional factor to consider is the change in attitude of the satellite with respect to the ground stations during a pass. The satellite nominally points towards the geocentre, but at lower elevation angles, the spacecraft is viewed side on with a look angle. This change in attitude affects the shape, size and effective gain of the antenna pattern.
2.7. Summary

This chapter has described the many factors which impact upon the performance of the LEO communications link. These factors were classified into the medium of propagation, terrain configuration, the satellite orbit, space environment and structure of the satellites. Some of these factors are deterministic and predictable, for example, Doppler shift and path loss and can be solved by careful system design. However, as the satellite traverses through the atmosphere and its elevation angle varies during its transit, the propagation conditions are variable. These unpredictable events such as multipath fading, interference and signal attenuation from the atmosphere are usually modelled with statistical or empirical models. These various channel models based on a literature survey are reviewed further in Chapter 3. The novel research areas in gathering in-orbit measurements from a LEO microsatellite, analysis of results and characterising the LEO satellite channel in terms of generative models will be described and presented.
Chapter 2: The specifics of satellites in low Earth orbit

2.8. References


3.1. Introduction

The communication link is the most critical factor in the transmission of a signal. The availability of
the link determines the achievable throughput and resulting message delay. The time-varying behaviour
of the link has to be carefully considered when selecting a modulation scheme, access and error
protection techniques. Furthermore, a judicious margin in the link budget might raise the cost of a
system, especially in a small power-limited satellite platform. For these reasons, it is essential to
thoroughly investigate the time-varying statistics of the channel. Much research has focused on channel
modelling techniques. Channel models are widely used to investigate and simulate appropriate
modulation, coding and access schemes. These models will also facilitate the design of a propagation
simulator.

This chapter reviews the standard fading channels adopted in numerous textbooks for the ground-based
terrestrial channel and mobile satellite channels. A comprehensive literature review covers the various
channel modelling techniques employed to characterise different fading environments, which include
statistical distributions, empirical methods and state-oriented models.
Chapter 3: LEO Channel Measurements and Channel Characterisation

Additionally, the current research in characterising the LEO satellite channel is covered and found to be inadequate.

A LEO UHF measurement campaign from a LEO microsatellite was therefore carried out at the University of Surrey. The analysis and results of the error statistics of the LEO UHF channel for a broad range of elevation angles are presented here. As it was necessary to produce a suitable channel simulator, several candidate generative models, using Markov chains to describe the observed error statistics of the channel, are examined. They include the Gilbert model, multiple-state Fritchman model and a proposed four-state Markov model. All results are presented and comparisons when matching our experimental data with that generated by these models are detailed.

3.2. Fading Channels

In contrast with fading channels, the GEO satellite channel is normally modelled as Additive White Gaussian Noise (AWGN). The geostationary satellite at an altitude of 35786.1 km above the equator appears at a quasi-fixed location and the link is not subject to large variations in Doppler shift or path loss. Moreover, the GEO satellite can be continuously accessed by all ground stations within its footprint. In the literature, the fading phenomenon is well documented and is reviewed as follows. A reduction in the signal amplitude is called a fade. Long-term fading is typically caused by relatively small-scale variations in topography along the propagation path, while short-term fading is typically caused by the reflectivity of various types of signal scatterers, both stationary and moving [Parsons92].

Rayleigh fading occurs when a receiver operates in an environment where the received signal is derived from a series of reflections from a number of nearby objects, and there is not a significant direct path between the receiver and the transmitter. Associated with each signal path is a propagation delay and an attenuation factor, both time-varying according to the medium of propagation. The received signal is therefore the sum of all the time-variant vectors having amplitudes and phases of different rates varying randomly. The Rayleigh envelope probability distribution \( p(r) \) may be described by Equation 3-1 where \( r \) represents the signal envelope of variance \( \sigma^2 \):

\[
p(r) = \frac{r}{\sigma^2} \exp \left[ -\frac{r^2}{2\sigma^2} \right]
\]  

(3-1)

For a link communicating with the satellite, when there is an additional line-of-sight component as well as a multipath component, Rician fading occurs. The Rician envelope probability distribution is described by:

\[
p(r) = \frac{r}{\sigma^2} \exp \left[ -\frac{(r^2 + A_c^2)}{2\sigma^2} \right] J_0 \left( \frac{r A_c}{\sigma^2} \right)
\]  

(3-2)

where \( r \) represents the signal envelope, \( A_c \) is the line-of-sight component and \( J_0(.) \) is the modified Bessel function of zeroth order.
Shadowing is the attenuation of the direct path caused by obstacles in the propagation path, for instance, roadside trees, buildings, hills and mountains. Shadowing increases with carrier frequency and is therefore more marked at L-band than at UHF. Measurements have been performed on the amount of roadside tree attenuation at UHF for land-mobile satellite systems and these indicate that shadowing is the most dominant factor determining signal fading.

Although there is no comprehensive mathematical formula for shadowing, a log-normal distribution has been found to best fit the experimental data. The log-normal/shadowing envelope probability distribution $p(r)$ is represented by:

$$p(r) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[ -\frac{(\ln r - \mu)^2}{2\sigma^2} \right]$$

where $r$ is the signal envelope and $\mu$ is the mean.

3.2.1. The terrestrial environment

It is well-documented that the terrestrial mobile radio channel can be modelled as Rayleigh with its local mean following lognormal statistics with uniform phase distribution [Suzuki77].

![Figure 3-1: The Terrestrial network](image)

Signals in the terrestrial environment are subject to propagation path losses, which comprise free space losses and terrestrial losses. Terrestrial losses are greatly affected by the general topography of the terrain and radio-wave scatterers along the path. The texture and roughness of the terrain tend to dissipate the propagated energy, hence reducing the received signal strength. Generally, the signal strength transmitted from the base station decreases with distance along a path leading away from the base station. Propagation between a mobile unit and a base station is most susceptible to the effects of multipath fading phenomena because all communications is essentially at ground level.

3.2.2. The mobile satellite channel

A mobile satellite system (MSS) is a satellite-based communications network that provides voice and data communications to mobile users throughout a vast geographical area. Its operation is similar to that of a cellular mobile network in which lines-of-sight of ground-based transmitting towers can
communicate with each other. The difference is that the satellite system, with its relay tower effectively placed at the parking orbit for GEO, and the recently proposed MEO and LEO orbits, can extend the effective line of sight substantially.

In mobile satellite systems, the signal from a satellite may reach the receiver via three different paths; namely a direct path, reflected or specular paths from the ground and diffuse components due to terrain discontinuities. These paths are illustrated in Figure 3-2. The direct path propagates through the atmosphere, subjected to Faraday rotation, scintillation and delay in the signal. Relative to the direct component, the effects of ground reflections can be reduced by increasing the directivity of the receiving terminal antenna. Therefore, the impact from ground reflections can be neglected.

A major uncertainty at present is what statistical distribution the diffuse component for the land mobile case will prove to be. At present, the diffuse component is assumed to be Rayleigh distributed and with a root mean square level which is 8 to 14dB below the direct ray level. The vector sum of the diffuse component and direct path affected by free space attenuation and atmosphere is represented by a Rician distribution.

![Image of propagation model for mobile satellite channels](image)

Mobile satellite systems have until now been restricted to geostationary orbit satellites. Increasingly, this network has been expanded to include the constellations of low earth orbit satellites and intermediate circular orbit satellites. For systems employing LEOs and MEOs, the fading behaviour of the channel needs to be properly characterised as much of the available data gathered was from geostationary satellites.

3.3. Literature Review on Channel Characterisation Techniques

Numerous strategies have been employed in the attempt to characterise the different fading environments previously discussed. These are categorised into empirical regression fits to data or statistical approaches that utilise probability density functions or a state-oriented representations of fades. The empirical regression fits-to-data model describes probability distributions of fades based on
Chapter 3: LEO Channel Measurements and Channel Characterisation

Experimental measurements. The first approach described in statistical modelling attempts is associated with one or several combinations of statistical probability density functions (Rayleigh, Rice, Lognormal) and relating its model parameters to possible environment configurations and elevation angle combinations. No attempt is made to describe in greater detail the extent of the shadowing and fading features of the received signal. On the other hand, the state-oriented approach describes in more detail the durations in shadowing and fading phenomena.

Table 3-1 summarises the work done in modelling the channel with statistical or empirical approaches.

<table>
<thead>
<tr>
<th>No</th>
<th>Year</th>
<th>References</th>
<th>Model Used</th>
<th>Channels Considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1977</td>
<td>Suzuki [Suzuki77]</td>
<td>Rayleigh-lognormal for terrestrial communications</td>
<td>Urban radio propagation medium</td>
</tr>
<tr>
<td>2</td>
<td>1985</td>
<td>Chun, Loo [Lo085]</td>
<td>Lognormal and Rayleigh correlated model under shadowing conditions for rural environments</td>
<td>Inmarsat Marecs-A satellite, 1542MHz in rural and suburban, 870MHz rural area</td>
</tr>
<tr>
<td>4</td>
<td>1992</td>
<td>Butt, Evans [Butt92]</td>
<td>Lutz, with improvements to shadowing coefficients</td>
<td>2 Inmarsat satellites at 63 East and 18.5West</td>
</tr>
<tr>
<td>7</td>
<td>1993</td>
<td>Sforza, Buonomo [Sforza93]</td>
<td>Statistical model utilising probability density functions</td>
<td>Non-geostationary L-and S-bands</td>
</tr>
<tr>
<td>8</td>
<td>1994</td>
<td>Corazza, Vatalaro [Corazza94]</td>
<td>Rice and lognormal statistics for all environments and orbits. Shadowing affects direct and diffuse components</td>
<td>L-band rural tree-shadowed environment</td>
</tr>
<tr>
<td>10</td>
<td>1997</td>
<td>Fontan, Gonzalez [Fontan97]</td>
<td>Three-state Markov chain</td>
<td>S-band from plane to vehicle</td>
</tr>
<tr>
<td>11</td>
<td>1973</td>
<td>Trafton, Blank &amp; McAllister [Trafton73]</td>
<td>Trafton, Blank and McAllister discrete Markov model</td>
<td>End-to-end satellite links with ground link segments of wirelines, combined microwave and wideband cable</td>
</tr>
<tr>
<td>12</td>
<td>1969</td>
<td>Tsai [Tsai69]</td>
<td>Fritchman Markov chain</td>
<td>HF radio</td>
</tr>
<tr>
<td>13</td>
<td>1975</td>
<td>Sastry [Sastry75]</td>
<td>Fritchman Markov chain</td>
<td>Satellite link with ground link segments of HF and troposcatter</td>
</tr>
<tr>
<td>14</td>
<td>1994</td>
<td>Swarts, Ferreira [Swarts94]</td>
<td>Fritchman Markov chain</td>
<td>VHF, moving vehicle in urban and freeway</td>
</tr>
<tr>
<td>16</td>
<td>1988</td>
<td>Chouinard, Lecours [Chou88]</td>
<td>Gilbert and Fritchman</td>
<td>UHF mobile radio channel, BS and mobile receiver</td>
</tr>
<tr>
<td>17</td>
<td>1991</td>
<td>Semmar, Lecours [Semmar91]</td>
<td>Fritchman Markov chain</td>
<td>UHF 910MHz, BS and mobile receiver in urban areas</td>
</tr>
<tr>
<td>18</td>
<td>1998</td>
<td>Kanatas et. al. [Kanatas98]</td>
<td>Empirical model</td>
<td>1.8MHz in Athens</td>
</tr>
</tbody>
</table>

Among the researchers that have adopted solely statistical probability density based functions to describe signal variations are Suzuki, Corazza and Loo [Suzuki77,Corazza94,Lo85]. Corazza proposed a combination of Rice and lognormal statistics for land mobile satellite channels that can be adapted to all types of environment by simply tuning the model parameters.

On the other hand, Loo proposed a statistical model for a rural environment where, for most of the time, a line-of-sight signal component is available at the receiver. The model describes the statistics in
terms of the probability density function of the line-of-sight component. Under foliage attenuation (shadowing), the model is lognormal distributed while the multipath interference is described as Rayleigh distributed.

A number of researchers have worked mainly on state-oriented discrete models. For example, channel states are related to the presence or absence of shadowing conditions with transition probabilities between the states. A two-state Markov model represents instances when the channel is shadowed (bad) or non-shadowed (good) [Rice97]. Other computationally demanding models consist of more than two states [Tsai69,Swarts94,Semmar91,McMan70].

Others employed a combination of the probability density functions to describe signal variations with discrete $M$-state Markov models [Vucetic92,Lutz91]. In the latter, Lutz distinguished between time intervals with high received signal power (or good channel state) and time intervals with low power level (bad channel state). Periods of the received signal power above or below a threshold classify the channel as good or bad for those periods.

A survey of existing literature has shown little development in modelling the LEO satellite channel. Most of the work describing the LEO channel has been derived from measurements made in the mobile satellite environment with GEO satellites. This is not likely to hold true for the LEO satellite channel. As far as the author is able to glean from the literature, the only research performed in obtaining propagation measurements is currently being pursued by SSTL at the University of Surrey and at DLR, the German Aerospace Research Establishment [Jahn94]. In SSTL, a number of experimental satellites have been launched to investigate propagation effects on LEO satellite communications. For example, the S80/T microsatellite is currently investigating the interference characteristics of the VHF LEO frequency allocations.

DLR, in co-operation with Inmarsat, has performed some L- and S-band measurement campaigns for channel effects to low earth orbit satellite systems [Jahn94]. The measurements have indicated that shadowing effects occur at very low elevation angles of 10 to 20 degrees, with fade depths of up to 20dB.

Due to the lack of a suitable channel model to describe the LEO satellite channel and insufficient channel parameters, it is therefore necessary to conduct measurements to obtain first-hand information about the time-varying statistics of the channel. Specifically, we are interested in the error patterns of the channel, which are obtained as described in the following section.
3.4. **Low Earth Orbit UHF Measurement Campaign**

This section describes the UHF measurement campaign that was performed at the SSTL Operations and Mission Control Groundstation at the University of Surrey. The groundstation is located at 51°N, 1°W in Guildford, Surrey. The setup of the measurement system is described and the analysis of the data in terms of burst statistics, i.e. burst lengths and burst gaps are presented.

UoSAT-3 was launched in 1990 on the ASAP Ariane V35. It resides in a 800 km sun-synchronous orbit at an inclination of 98°. Table 3-2 below summarises the orbital characteristics of UoSAT-3.

<table>
<thead>
<tr>
<th>INCLINATION</th>
<th>98.6°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eccentricity</td>
<td>0.0011</td>
</tr>
<tr>
<td>Mean Motion</td>
<td>14.298 revolutions/day</td>
</tr>
<tr>
<td>Perigee</td>
<td>784.6 km</td>
</tr>
<tr>
<td>Apogee</td>
<td>800.3 km</td>
</tr>
<tr>
<td>Orbital Period</td>
<td>100.714 minutes</td>
</tr>
</tbody>
</table>

Table 3-2: Orbital characteristics of UoSAT-3

The diagram shows the hardware of the transmitting end. The input to the satellite scrambler is held at a constant logic “1”. The operation of the scrambler is described by the polynomial $1 + X^{12} + X^{17}$ which will output a scrambling sequence that is transmitted on the downlink.

![Figure 3-3: Block diagram of transmitter](https://example.com/figure3-3.png)

These recordings were performed on the UHF downlink 435MHz channel, to be received by a 16 dBi 19/20 turn helix tracking antenna located at the roof of the Electrical Engineering building. At the receiver, the continuous scrambling sequence is then demodulated, descrambled with the same scrambling polynomial and recorded using a data acquisition card.

![Figure 3-4: Block diagram of receiver](https://example.com/figure3-4.png)

A detailed schematic of the receiver architecture is depicted in Figure 3-5. On the downlink, two UHF helix antennas, using left and right hand circular polarisation, are employed. The signal is fed via coaxial cable to the Low Noise Amplifier (LNA) at the front end of the receiver. On the UHF downlink path, there are two stages of filtering. The first on the masthead directly after the helix antenna. A 11MHz helical Wide Band Pass filter is used and is fed to a high-gain wide bandwidth LNA with a gain...
of typically 30-32dB and a noise figure of 1.4. The second stage of filtering is achieved in the groundstation. A 2MHz Narrow Band Pass Filter is employed to obtain excellent frequency selection with minimum insertion loss. After amplification and filtering, the signal was down-converted in the VHF/UHF transceiver, demodulated at the rate of 9.6kbps and de-scrambled.

At the heart of the groundstation is a tracking computer running software for real-time prediction. The tracking software calculates the azimuth and elevation angles for antenna pointing. The groundstation employs a high precision, robust bi-axial rotator system to ensure accurate satellite tracking during passes. Apart from the VHF/UHF antennas, a 2m S-band dish is used to track downlink signals from the UoSAT-12 minisatellite.

Direction related information is supplied to the rotator control via an RS232C interface from the controller unit in the groundstation which is commanded by the tracking software running on the tracking computer. An IBM-compatible personal computer was used for data logging. A data acquisition card was purchased to acquire, store and write the data to disk.
The data stored during each satellite pass includes the sampled received signals, elapsed time, elevation angle and azimuth. The format of the data is as follows.

\(<\text{TIMESTAMP}\> <\text{AZIMUTH}\> <\text{ELEVATION}\> <\text{LENGTH}\> <\text{DATA}\>

Each of the measurements last for a duration of approximately 10 to 15 minutes, which corresponds to when signal acquisition was achieved, the whole satellite pass and until loss of signal. The uncompressed ASCII file size for each satellite pass was in the order of 150 to 180 Mbytes. The signals from the demodulator were sampled at ten times the bit rate by the data acquisition card and logged. A program was written to extract the relevant data, by first decimating the sampled points by ten and scrambling the whole sequence again to recover the original error patterns.

The operations of the scrambler and de-scrambler are depicted as follows.

![Shift register polynomial](image.png)

Due to the scrambling operation, error propagation occurs, i.e. one erroneous bit at the input would cause two extra error bits at the output. In effect, the number of errors increases threefold compared to the original error sequence. In a perfect channel, the output from the ground de-scrambler will be continuously one, but in a real channel, a number of zeros would indicate the presence of errors.
3.4.1. Average Bit Error Rate

The average bit error rate is the ratio of the total number of errors to the total number of bits transmitted. It is an important first-order statistic, but does not contain any information about the occurrence of errors.

3.4.2. Burst distribution

A burst is assumed to begin with an error and end with an error. The error burst is defined with respect to a specified value of error density $\Delta_0$. If the ratio of the number of errors to the total number of bits in a region of interest exceeds this specified $\Delta_0$ density, the region considered is defined as a burst. If the successive inclusion of the next error keeps the density above the specified value, the burst is continued and the burst ends if further inclusion of an error reduces the density below the specified value. This is easily illustrated with the following example. Let '1' represent an error while '0' represents a correct bit. The specified density is $\Delta_0 = 0.5$. We assume that the first '1' does not belong to a previous burst. Say, we have the following sequence

\[ \ldots 0 0 0 1 1 0 0 1 0 1 0 0 0 1 \ldots \]

Start from the first error. If the second error is included, the density is 1; if the third error is included, the density is 3/5; with the fourth error, the density is 4/7; if the fifth error is included, the density is 5/11 which is less than 0.5. Therefore, the burst ends at the fourth error, with a burst length of 7.

3.4.3. Burst interval (or Gap) distribution

A burst interval is the region between two bursts; it begins with a correct bit preceded by the last error of the preceding burst, and ends with a correct bit followed by the first error of the succeeding burst. The error density of a burst interval must be less than the prescribed density, $\Delta_0$, chosen for defining the burst. In this thesis, the burst interval will be replaced by the notation of gaps.
3.4.4. Error-free run distribution

The error-free run distribution is defined as the probability of an error-free run of length at least \( m \) following an error, \( P(0^m/1) \), versus the length \( m \).

\[
P(0^m/1) = 1, \quad m = 0.
\]  

(3-4)

The error-free run distribution can be calculated from the gap-between-errors distribution.

3.4.5 Gap-between-errors distribution

The gap-between-error is a region of error-free bits between two errors; the length of the gap-between-error is the number of those error-free bits. The gap-between-error distribution is the plot of the cumulative relative frequency of the gap-between-error length \( m \) versus the length \( m \).
3.5. **Statistics of LEO UHF burst conditions**

The analysis of the error sequences of the LEO UHF channel has shown useful and interesting results for a range of elevation angles. These results have been grouped into three categories of elevation angles ranging from 15° and below, from 20° to 63° and from approximately 70° to nearly 90°, based upon the similarities shown in their error statistics. All results are plotted and analysed in terms of histograms, cumulative histograms, average bit error rate in the channel and throughput performance of the existing SR protocol.

3.5.1. **Histograms of Burst lengths and burst gaps**

At an elevation angle of 10°, the channel is discovered to be very bursty and the estimated average bit error rate is $4.97 \times 10^{-2}$ for nearly 1M of samples. The bursts can reach up to a maximum of 3500 bits while 90% of the bursts are less than 5 bits. On the other hand, the maximum gap length is 8000 bits with 95% of the gaps being less than 100 bits. A mere 4.2% of the 256 byte-length packets were recovered through the SR protocol. Based on these results, it is clear that reliable communications cannot be achieved at this low elevation angle.
Chapter 3: LEO Channel Measurements and Channel Characterisation

For a satellite pass at 15°, the channel conditions are found to have improved. The length of the bursts has reduced and the maximum burst length is 85 bits, with 95% of the bursts being less than 5 bits. The maximum gap length is 23573 bits with 97% of the gaps less than 2000 bits.

For elevation angles from 20° to 40°, it is discovered that the channel exhibits long periods of good reception with the occasional short bursts which are predominantly random. A huge proportion (90%) of the bursts are in the order of less than five bits and can be considered as AWGN. Analysis of the error statistics has revealed that the maximum burst length is 30 bits while the maximum gap length reach up to 153 kbits. As the current system transmits at data rates of 9.6 kbit/s, this implies that there is perfect reception for up to 16 seconds.

All histograms depict the burst distributions for satellite passes at 15°, 23°, 30°, 40°, 52°, 63°, 74° and 80°. For all elevation angles considered, it is observed that the histograms seem to follow the shape of a rapidly decaying exponential with a majority of very short bursts and as the burst lengths increase, the numbers drop considerably. These results are further demonstrated in Graphs 3-1i and 3-1j.

An interesting phenomenon is observed at a satellite pass of 52° for all samples of data analysed. At this elevation angle subject to the effect of interference, the bursts are longer, more frequent and are clustered, while the length of the gaps reduces. Further analysis has shown that the maximum gap length is in the order of 4617 bits while the bursts can vary up to a maximum of 177 bits.
There are two speculations as to why interference exists at this particular elevation angle. The first is, a radio signal from a nearby source at the same frequency which intervenes with perfect reception of the satellite downlink signal. However, as this effect is observed on each pass regardless of satellite azimuth, this argument does not quite hold. The second reasoning is based on interfering effects amongst the satellite antennas. The UoSAT-3 UHF antennas are mounted on the four corners of the satellite earth-facing facet whilst the VHF antenna is located at the centre of this facet. The VHF antenna could potentially cause a dip in the UHF antenna gain plots, as observed in more recent missions such as PicoSAT that is built for the US Air Force.

Graph 3-1i: Burst histogram comparisons from 15° to 40°

Graph 3-1j: Burst histogram comparisons from 52° to 74°
At a 63° satellite pass, the channel is very quiet and the gap statistics are better than those previously encountered at the elevation angles from 10° to 52° thus far. The maximum burst length is evaluated to be 7 bits with 97.5% of the bursts of length 1 bit. The gaps reach a maximum of 200000 bits with 50% of the gaps less than 2000 bits and 80% less than 10000 bits.

At satellite passes of 74° and above, the error statistics gradually turns bursty again. The number of bursts increases significantly while the gap lengths reduce dramatically. For each data sample measured and analysed at 74°, 80° and nearly 90°, it is observed that when the satellite is directly overhead, there is a consistent burst clustering phenomena. The maximum burst for this range can reach up to 85 kbits, which is equivalent to a period of 9 seconds. In effect, this implies that up to 42 packets can be rejected by the Selective Repeat (SR) PACSAT Broadcast protocol.

The graphs above compare the histogram of gap lengths with various elevation angles. For all elevation angles, the gap histograms seem to exhibit the shape of an exponential distribution as well. A majority of the gaps are short gaps and as the lengths increase, the number of such gaps reduce. Through observing the cumulative plots at 15°, 20°, 30° and 40°, it is noted that as the elevation angle increases, the number of long gap lengths also increases.
For a satellite pass at 52°, the effects of interference are examined. It is discovered at this elevation angle that there is an increase in the number of very short gaps (of less than 100 bits). However, at the high elevation pass of 63°, there is a significant change in the channel conditions. The gaps are very long and the maximum 200000 bits gap implies that there is perfect reception of the packets up to a duration of 98 seconds.

At elevation angles from 74° to nearly 90°, it is observed from the histograms that there is a large count in the number of short gaps (of less than 100 bits). All samples of data taken for these elevation angles have displayed a non-random clustering of bursts, which are further elaborated in Section 3.5.3.

Graphs 3-2i and 3-2j are plot in log scales and highlight the differences in the gap histograms for all elevation angles.
3.5.2. Average Bit Error Rate

Table 3-3 lists the average bit error rates of the LEO UHF channel for all elevation angles, based on the number of samples obtained. The average bit error rate has been evaluated as the ratio of the total number of errors to the total number of bits transmitted within the range of elevation angles taken into consideration. It can be generalised to say that the average bit error rate in the channel decreases as the elevation angle increases. However, there are two exceptions to this claim. The first is that, when the
channel is subject to the effects of unpredictable interference (which can occur at any instant and elevation angle as demonstrated for a 52° satellite pass), the average bit error rate is severely affected. Secondly, at the very high satellite elevation passes from 74° to nearly 90°, the non-random clustering of bursts increases the average bit error rate.

Table 3-3: Average Bit Error Rate for a range of satellite elevation angles

<table>
<thead>
<tr>
<th>RANGE OF ELEVATION ANGLES</th>
<th>TOTAL NUMBER OF SAMPLES TAKEN</th>
<th>AVERAGE BIT ERROR RATE</th>
</tr>
</thead>
<tbody>
<tr>
<td>8° - 10°</td>
<td>777726</td>
<td>4.97 × 10⁻²</td>
</tr>
<tr>
<td>12° - 15°</td>
<td>1818662</td>
<td>3.4 × 10⁻³</td>
</tr>
<tr>
<td>19° - 23°</td>
<td>2071546</td>
<td>2.83 × 10⁻⁴</td>
</tr>
<tr>
<td>27° - 30°</td>
<td>1141838</td>
<td>4.79 × 10⁻⁴</td>
</tr>
<tr>
<td>36° - 40°</td>
<td>1530549</td>
<td>1.04 × 10⁻⁴</td>
</tr>
<tr>
<td>44° - 47°</td>
<td>790496</td>
<td>1.05 × 10⁻³</td>
</tr>
<tr>
<td>48° - 52°</td>
<td>380640</td>
<td>1.1 × 10⁻²</td>
</tr>
<tr>
<td>59° - 63°</td>
<td>930812</td>
<td>8.27 × 10⁻⁵</td>
</tr>
<tr>
<td>71° - 74°</td>
<td>658926</td>
<td>6.0 × 10⁻³</td>
</tr>
<tr>
<td>80° - 90°</td>
<td>800000</td>
<td>8.6 × 10⁻²</td>
</tr>
</tbody>
</table>

3.5.3. Cumulative Histograms of Burst lengths and burst gaps

In this section, the cumulative burst lengths and burst gaps of the various range of elevation angles considered are plotted and the results are discussed.

Graphs 3-3a and 3-3b depict the cumulative histograms for a satellite pass at 15°. It is observed that 92% of the bursts are in the order of 5 bits or less while approximately 97.1% of the gaps are less than 2000 bits. This implies that multiple bursts could occur within a packet of 256 bytes.

Graphs 3-4a and 3-4b depict the cumulative histograms for a satellite pass at 23°. It is observed that 95% of the bursts are in the order of 5 bits or less while approximately 79% of the gaps are less than 2000 bits. This again implies that multiple bursts could occur within a packet of 256 bytes. In comparison with the cumulative gap histograms obtained for the 15° pass, the conditions of the channel have improved as demonstrated in the increase in the number and lengths of the gaps.
For a satellite pass of 40°, the cumulative histograms of the bursts and gaps follow a similar distribution to a 23° pass. Approximately 95% of the bursts are less than 7 bits while 55% of the gaps are less than 2000 bits. There appears to be a slight decrease in the number of long gap lengths. Again, this implies that multiple bursts could occur within one packet.
From Graphs 3-6a and 3-6b above, we observe for a 52° satellite pass that 95% of the bursts are less than 10 bits while 99.4% of the gaps are less than 1200 bits. The result obtained for this elevation angle exhibits clearly that during the effects of interference, the channel is very bursty and there is few good intervals. The statistics obtained for a 63° satellite pass are similar to the error statistics encountered in the 23° to 40° satellite passes.

As demonstrated in the above histograms, for an 80° satellite pass, approximately 97% of the bursts are in the order of less than 100 bits while 98% of the gaps are less than 400 bits. For comparison purposes, we are interested in the how the burst lengths and gaps vary for the whole range of elevation angles as depicted in Graphs 3-8 and 3-9. The results previously discussed are summarised in the graphs below, which compare the cumulative burst histograms and cumulative gap histograms for all elevation angles. Based upon the results obtained, it can be concluded that the error statistics tend to be more bursty in nature than random at the higher elevation angles.
This result is the opposite to what was expected at the higher elevation angles where line-of-sight with the satellite is more likely to occur and in this case, the channel conditions would have been expected to be better. Such results indicate a significant amount of satellite influence upon the radio path.

A link budget calculation was made to determine the link margin as the satellite traverses from horizon to zenith as illustrated in Table 3-4. The antenna gain is as measured from the UoSAT-3 UHF antenna on-board the satellite. The UoSAT-3 antenna is beam-shaped to compensate for the variations in FSL from horizon to zenith. This FSL variation in the link is approximately 12 dB for UoSAT-3. This means that there is higher antenna gain at horizon than at zenith and ideally, the link margin should remain constant throughout the pass. However, the shape of the antenna gain actually gives 8 dB less link margin compared to the horizon. This is because there is an approximately 20 dB null in antenna gain at zenith. In the calculations of the link margin, the downlink satellite power from UoSAT-3 was approximately 3 W. In subsequent microsatellites built later like HealthSat-2, this transmitting power has increased to 7 W.

<table>
<thead>
<tr>
<th>ELEVATION ANGLE</th>
<th>0°</th>
<th>5°</th>
<th>10°</th>
<th>20°</th>
<th>30°</th>
<th>40°</th>
<th>50°</th>
<th>60°</th>
<th>70°</th>
<th>80°</th>
<th>85°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downlink power dBW</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
<td>3.00</td>
</tr>
<tr>
<td>Antenna gain dBi</td>
<td>1.00</td>
<td>1.50</td>
<td>1.50</td>
<td>2.00</td>
<td>3.00</td>
<td>3.00</td>
<td>2.00</td>
<td>-3.00</td>
<td>-8.00</td>
<td>-12.00</td>
<td>-18.00</td>
</tr>
<tr>
<td>EIRP dBW</td>
<td>4.00</td>
<td>4.50</td>
<td>4.50</td>
<td>5.00</td>
<td>6.00</td>
<td>6.00</td>
<td>5.00</td>
<td>0.00</td>
<td>-5.00</td>
<td>-9.00</td>
<td>-15.00</td>
</tr>
<tr>
<td>Range km</td>
<td>3293.2</td>
<td>2783.9</td>
<td>2366.9</td>
<td>1768.7</td>
<td>1395.2</td>
<td>1158.9</td>
<td>1006.2</td>
<td>907.2</td>
<td>845.15</td>
<td>810.9</td>
<td>802.7</td>
</tr>
<tr>
<td>FSL dB</td>
<td>154.9</td>
<td>153.4</td>
<td>152.0</td>
<td>149.5</td>
<td>147.4</td>
<td>145.8</td>
<td>144.6</td>
<td>143.7</td>
<td>143.0</td>
<td>142.7</td>
<td>142.6</td>
</tr>
<tr>
<td>Ionospheric losses dB</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
<td>-1.00</td>
</tr>
<tr>
<td>Tropospheric losses dB</td>
<td>-0.45</td>
<td>-0.11</td>
<td>-0.06</td>
<td>-0.03</td>
<td>-0.03</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.02</td>
<td>-0.01</td>
<td>-0.01</td>
</tr>
<tr>
<td>Polarisation losses dB</td>
<td>-3.00</td>
<td>-3.00</td>
<td>-3.00</td>
<td>-3.00</td>
<td>-3.00</td>
<td>-3.00</td>
<td>-3.00</td>
<td>-3.00</td>
<td>-3.00</td>
<td>-3.00</td>
<td>-3.00</td>
</tr>
<tr>
<td>Fade margin dB</td>
<td>-2.00</td>
<td>-2.00</td>
<td>-2.00</td>
<td>-2.00</td>
<td>-2.00</td>
<td>-2.00</td>
<td>-2.00</td>
<td>-2.00</td>
<td>-2.00</td>
<td>-2.00</td>
<td>-2.00</td>
</tr>
<tr>
<td>Rx signal dBW</td>
<td>-157.31</td>
<td>-155.01</td>
<td>-153.55</td>
<td>-150.49</td>
<td>-147.42</td>
<td>-144.75</td>
<td>-142.00</td>
<td>-139.57</td>
<td>-137.54</td>
<td>-135.70</td>
<td>-133.86</td>
</tr>
<tr>
<td>Receiver C/T dB/K</td>
<td>-12.35</td>
<td>-12.35</td>
<td>-12.35</td>
<td>-12.35</td>
<td>-12.35</td>
<td>-12.35</td>
<td>-12.35</td>
<td>-12.35</td>
<td>-12.35</td>
<td>-12.35</td>
<td>-12.35</td>
</tr>
<tr>
<td>C/N system dB</td>
<td>17.19</td>
<td>19.49</td>
<td>20.95</td>
<td>24.01</td>
<td>27.07</td>
<td>28.69</td>
<td>28.92</td>
<td>24.82</td>
<td>20.44</td>
<td>18.60</td>
<td>10.88</td>
</tr>
<tr>
<td>C/N required dB</td>
<td>13.50</td>
<td>13.50</td>
<td>13.50</td>
<td>13.50</td>
<td>13.50</td>
<td>13.50</td>
<td>13.50</td>
<td>13.50</td>
<td>13.50</td>
<td>13.50</td>
<td>13.50</td>
</tr>
<tr>
<td>Margin dB</td>
<td>3.69</td>
<td>5.99</td>
<td>7.45</td>
<td>10.51</td>
<td>13.57</td>
<td>15.19</td>
<td>15.42</td>
<td>11.32</td>
<td>6.94</td>
<td>3.30</td>
<td>-2.62</td>
</tr>
</tbody>
</table>

Figure 3-9: UoSAT-3 UHF Antenna Pattern

It is observed from Table 3-4 that the link margin is negative at elevation angles of 85° and above. It is suspected that at the very high elevations, the satellite traverses rather rapidly across the sky and hence the high-gain groundstation antennas may not be following it accurately. This will be dependent upon the control step update rate, the antenna pointing accuracy, orbit element or prediction accuracy and timing errors.
Investigations into these aspects have revealed that the high gain UHF helix antenna is able to track at a 1.80/s rate and pointing accuracy of +/-3°. In terms of orbital element prediction accuracy, the NORAD Two Line Keplerian elements prediction software at the groundstation is updated daily.

3.6. Generative models

In this section, we review different generative models using Markov chains, for analysis of the error processes and error gap processes. This is the state-oriented statistical approach to modelling the shadowing and fading behaviour of the channel in greater detail, as discussed. The generative channel model is a Markov chain consisting of a finite or infinite number of states with defined transition probabilities. The transitions among the states produce a state sequence. Such models attempt to simulate the transitions in real channel behaviour from good to bad and vice versa. The model, when suitably parameterised using typical error data from real channels, can be used to derive statistics which are relevant to evaluating the performance of error control schemes. In the quest to develop models that adequately represent real channel behaviour and that are mathematically tractable, efforts in generative modelling took several directions. The broad range of attempts include an initial two-state Markov model, modifications to it, models with a larger number of good and bad states, finite-state Markov chains, infinite-state models and so forth. Several of the more commonly utilised generative models summarised in Table 3-5 will be examined to characterise the LEO UHF error sequences.

<table>
<thead>
<tr>
<th>NO.</th>
<th>PROPOSED BY</th>
<th>YEAR</th>
<th>FEATURES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gilbert</td>
<td>1960</td>
<td>Two-state Markov chain. Error digit can be generated only in one state with some probability (1-h)</td>
</tr>
<tr>
<td>2</td>
<td>Elliott</td>
<td>1963</td>
<td>Two-state Markov chain. Errors can be generated in either states.</td>
</tr>
<tr>
<td>3</td>
<td>Berkovits &amp; Cohen</td>
<td>1967</td>
<td>Three-state model, error gap distribution is sum of three exponential terms</td>
</tr>
<tr>
<td>4</td>
<td>McCullough</td>
<td>1968</td>
<td>Errors occur in all states. Transitions between states permitted after an error has occurred</td>
</tr>
<tr>
<td>5</td>
<td>Trafton et al.</td>
<td>1971</td>
<td>Similar to McCullough's. Transition probabilities are function of sojourn times in each states</td>
</tr>
<tr>
<td>6</td>
<td>Fritchman</td>
<td>1967</td>
<td>Finite-state Markov chain with k good states and N-k error states</td>
</tr>
<tr>
<td>7</td>
<td>Adoul etc.</td>
<td>1970</td>
<td>Two infinite-state Markov chains are coupled with transitions between the chains only after an error occurs and conditioned on the length of the previous gap</td>
</tr>
</tbody>
</table>
3.7. Modelling as Gilbert’s model and its extensions

Gilbert proposed an error generation model based on a two-state Markov chain [Gilbert60]. As illustrated in Figure 3-10, the model is composed of a good state ‘G’ and a bad or burst state ‘B’. A sequence of binary noise digits is generated digit by digit by the Markov chain. In state ‘G’, transmission is error free while in state ‘B’, the channel has a probability $h$ of transmitting a digit correctly. The error generation process is determined by the transition probabilities $P_{ij}$ from a state, at a given instant, to the subsequent state. The transition probabilities $(1-\beta)$ and $(1-\alpha)$ are small such that the probabilities of persisting in the ‘G’ and ‘B’ states are high, thus simulating burst noise conditions. The good state occurs with a low probability while the bad state occurs with a high probability.

$$\begin{bmatrix}
\beta & 1-\beta \\
1-\alpha & \alpha
\end{bmatrix}$$

Figure 3-10: Gilbert’s model and transition matrix

Gilbert has shown that his model approximates the burst noise on two of the calls from a field testing programme carried out by Bell Systems. Subsequently, Elliott suggested a modification to Gilbert’s model by introducing an extra parameter $k$, which is the probability of correct reception of a bit when the channel is in the good state. This means that errors can be generated in either of the states [Elliott63].

In the Gilbert model, the occupancy times for both good and bad states are exponentially distributed. The probability of residing in the good and bad state is equal to the reciprocal of the means of gap lengths and burst lengths respectively. In the attempt to characterise the LEO UHF error sequences, we initially employed the Chi-square goodness-of-fit test to establish if the measured data has been generated by a process characterised by a particular probability distribution. This test is accomplished by comparing the measured data’s frequency distribution to the hypothesised population counterpart, which in this case is the exponential distribution. In the analysis of the error sequences, it is assumed that $f_i$ are the actual frequencies from the measured channel data, where $i$ denotes each category. These will be compared to the expected frequencies denoted by $\hat{f}_i$.

$$\chi^2 = \sum_i \frac{(f_i - \hat{f}_i)^2}{\hat{f}_i}$$

(3-5)

The $\chi^2$ burst and gap values for each range of elevation angles have been computed based on Equation 3-5 and are displayed in Table 3-6 as follows.
Table 3-6: Chi-square comparison of the error sequences

<table>
<thead>
<tr>
<th>ELEVATION ANGLE</th>
<th>MEAN BURST LENGTH</th>
<th>MEAN GAP LENGTH</th>
<th>α</th>
<th>β</th>
<th>CHI² BURST COMPARISON</th>
<th>CHI² GAP COMPARISON</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>1.597</td>
<td>341.673</td>
<td>0.626</td>
<td>0.002927</td>
<td>3.139×10³</td>
<td>3.070×10³</td>
</tr>
<tr>
<td>23°</td>
<td>1.199</td>
<td>3959.66</td>
<td>0.834</td>
<td>0.000253</td>
<td>309.969</td>
<td>376.667</td>
</tr>
<tr>
<td>30°</td>
<td>1.398</td>
<td>2328.85</td>
<td>0.715</td>
<td>0.000429</td>
<td>331.232</td>
<td>507.178</td>
</tr>
<tr>
<td>40°</td>
<td>1.622</td>
<td>11335.65</td>
<td>0.616</td>
<td>8.82×10⁻⁵</td>
<td>109.636</td>
<td>304.191</td>
</tr>
<tr>
<td>52°</td>
<td>1.882</td>
<td>107.56</td>
<td>0.531</td>
<td>0.009297</td>
<td>2.022×10³</td>
<td>2.437×10³</td>
</tr>
<tr>
<td>63°</td>
<td>1.095</td>
<td>12577.22</td>
<td>0.914</td>
<td>7.95×10⁻⁵</td>
<td>4.4258×10³</td>
<td>7.581×10³</td>
</tr>
<tr>
<td>68°</td>
<td>1.644</td>
<td>193.82</td>
<td>0.608</td>
<td>0.005159</td>
<td>2.671×10³</td>
<td>3.243×10³</td>
</tr>
<tr>
<td>74°</td>
<td>18.685</td>
<td>42.13</td>
<td>0.054</td>
<td>0.023737</td>
<td>3.141×10³</td>
<td>2.515×10³</td>
</tr>
<tr>
<td>80°</td>
<td>29.126</td>
<td>49.61</td>
<td>0.034</td>
<td>0.020157</td>
<td>2.827×10³</td>
<td>2.515×10³</td>
</tr>
</tbody>
</table>

After the computation of the $\chi^2$ value, a decision is taken to establish whether the measured data follows an exponential distribution based on a selected significance level and acceptance and rejection regions. The calculation of $\chi^2$ has been performed for satellite passes ranging from 23° to 80° and several of the plots of the experimental bursts and gaps and their exponential curve approximation are illustrated in Graphs 3-11 to 3-14.

Graph 3-11: Histogram of bursts and exponential curve approximation at 23°.

Graph 3-12: Histogram of bursts and exponential curve approximation at 40°.
From the graphs above and calculation of $\chi^2$ it is evident that the burst lengths and the intervals between the bursts (gaps) does not correspond to an exponential distribution, as the $\chi^2$ values were too large. It is therefore concluded that the Gilbert model is not representative in describing the error statistics observed on the LEO UHF channel. Therefore, other generative models were investigated.
3.8. **Modelling as Fritchman's Partitioned Markov chain model**

Fritchman had investigated a generalisation of Gilbert's model, consisting of a finite $N$-state Markov chain, partitioned into a group (A) of $k$ error-free states and another group (B) of $N - k$ error states [Fritchman67]. Assuming a stationary Markov chain, Fritchman has derived a model for which the interval length distribution between errors is given by the sum of $k$ exponentials while the error bursts distribution is described by the sum of $N - k$ exponentials. The transition matrix and state diagram are shown in Figure 3-11.

\[
\begin{bmatrix}
0 & P_{1N} \\
P_{22} & P_{2N} \\
0 & \cdots \\
0 & P_{N-1,N-1} & P_{N-1,N} \\
0 & P_{N1} & P_{N2} & \cdots & P_{N,N-1} & P_{NN}
\end{bmatrix}
\]

Figure-3-11: Fritchman's partitioned Markov chain ($N-k=1$), and matrix of transition probabilities.

In the simplified version of Fritchman's model, transitions between different states are allowed only from a state belonging to one of the two groups, that is A or B, to a state from the other group. Within a group, the only possible transitions are from and to the same state. Fritchman had shown that a simple partitioned Markov chain model, in which there is only one error state and no transition between the error-free states, is uniquely determined by the error-free run distribution. The error-free interval length distribution $P(0^m|1)$ is expressed as:

\[
P(0^m|1) = \sum_{i=1}^{k} \alpha_i \beta_i^m
\]

(3-6)

and the error burst length distribution $P(1^m|0)$ is equal to:

\[
P(1^m|0) = \sum_{i=k+1}^{N} \alpha_i \beta_i^m
\]

(3-7)

where the values $\alpha_i$, $\beta_i$ are Fritchman's model parameters. The probability $P(0^m|1)$ of obtaining an interval length greater than or equal to $m$ bits can be related to the transition probabilities as follows:

\[
P(0^m|1) = \sum_{i=1}^{k} P_{N,i} \left( \frac{P_{i,j}}{P_{i,i}} \right)^m
\]

(3-8)
Therefore, the transition probabilities are related to Fritchman’s parameters by:

\[ P_{i,d} = \beta_i \]
\[ P_{i,N} = 1 - \beta_i \]
\[ P_{N,i} = \alpha_i \beta_i \]
\[ P_{N,N} = 1 - \sum_{i=1}^{k} \alpha_i \beta_i \] (3-9)

The above transition probabilities can be evaluated from experimental measurements of the interval lengths distribution through curve-fitting techniques. For a Markov chain consisting of a unique error state, there is no need to calculate the burst length distributions since the error generation process is completely defined by the set of transition probabilities corresponding to the error-free states. In many previous cases, it has been found that the error burst distribution is well described by a single exponential [Chou88, Semmar91]. This implies that a single error state is sufficient. As for the burst interval distribution length, Fritchman and others found that a model with \( k=2 \) or 3 exponential functions is generally sufficient.

![Graph 3-15: Gap-between-errors distribution for a 23° elevation pass](image)

The experimental interval length distribution \( P(0^m/1) \) is determined by computing the ratio of the intervals (or series of consecutive ‘0’ i.e. good bits) for which the length equals or exceeds \( m \), to the total number of intervals encountered within an observed error sequence. Similarly, we evaluate the error burst length distribution \( P(1^m/0) \) by considering this time, the proportion in the error sequence of the consecutive series of ‘1’ (bad bits) equal or greater than the burst length \( m \).
Chapter 3: LEO Channel Measurements and Channel Characterisation

3.8.1 Curve-fitting to error-free run distribution

A computer program is used to fit the error-free run distribution \( P(0^m/1) \) by a sum of exponential functions, and for our case, either two or three terms are required. The error-free run can be calculated from the Gap-between-errors distribution (for instance, in Graph 3-15 for \( 23^\circ \) elevation angle) as follows. Let \( N_g \) be the total number of gaps-between-error, \( N_g(m) \) the number of gaps-between-error of length \( m \), \( N_e \) the total number of errors, \( P_g(m) \) the gap-between-error distribution, and \( P(0^m/1) \) the error-free run distribution:

\[
P(0^i / 1) = \frac{N_g}{N_e} \quad \text{ (3-10)}
\]

\[
P_g(1) = \frac{N_g(1)}{N_g} \quad \text{ (3-11)}
\]

\[
P(0^2 / 1) = \frac{N_g - N_g(1)}{N_e} = \left[1 - P_g(1)\right] \frac{N_g}{N_e}
\]

\[
= \left[1 - P_g(1)\right] P(0^1 / 1) \quad \text{ (3-12)}
\]

\[
P_g(2) = \frac{N_g(1) + N_g(2)}{N_g} \quad \text{ (3-13)}
\]

\[
P(0^3 / 1) = \frac{N_g - \left[N_g(1) + N_g(2)\right]}{N_e}
\]

\[
= \left[1 - P_g(2)\right] P(0^1 / 1) \quad \text{ (3-14)}
\]

\[
P_g(m-1) = \frac{N_g(1) + N_g(2) + \cdots + N_g(m-1)}{N_g}
\]

\[
P(0^m / 1) = \left[1 - P_g(m-1)\right] P(0^1 / 1) \quad \text{ (3-15)}
\]

The error-free run distribution is approximated by the sum of exponential functions denoted by:

\[
A_1 e^{a_1 m} + A_2 e^{a_2 m} + \cdots + A_i e^{a_i m}
\]

\[
\text{ (3-17)}
\]

The interval length distributions for satellite passes at \( 23^\circ \) to \( 74^\circ \) are shown in Graphs 3-16a to 3-16f. Each error-free run distribution was plot from Equation 3-16 and the corresponding curve-fitting was achieved with the MATLAB simulation tool.
Chapter 3: LEO Channel Measurements and Channel Characterisation

For each error sequence for whole range of satellite passes, it is found that the burst intervals exceed 100000 bits while the maximum number of successive errors is of the order of 10 bits. Consequently,
the interval length distribution is calculated for interval lengths ranging from 1 to 100000 and the error burst length is computed for \( m \) ranging from 1 to 10 bits.

For illustration purposes, at a 23° satellite pass, the error-free run distribution can be approximated by the sum of two exponential terms where the parameters through curve fitting in Graph 3-16a were found to be:

\[
A_1 = 0.78, \quad a_1 = -0.0013, \quad A_2 = 0.1246, \quad a_2 = -0.00007
\]

The corresponding transition probability matrix and state diagram of the model is:

\[
\begin{bmatrix}
0.99870 & 0 & 0.00129 \\
0 & 0.99993 & 0.00007 \\
0.77899 & 0.12459 & 0.09642
\end{bmatrix}
\]

Figure 3-12: Fritchman's state diagram and matrix of transition probabilities for a 23° satellite pass

At satellite passes of 30° and 40°, the error-free run distribution can be described by the sum of three exponential terms. Within the interval length distribution curve for the error sequence, we were able to distinguish three different line segments. We can clearly distinguish a first slope for values of \( m \) smaller than 20 bits, and two other slopes within the curve, for values of \( m \) ranging from 20 to 5000 bits and when \( m \) exceeds 5000 bits.

\[
\begin{bmatrix}
0.9989 & 0 & 0 & 0.0011 \\
0 & 0.9999 & 0 & 0.0001 \\
0 & 0 & 0.9130 & 0.0861 \\
0.5294 & 0.2299 & 0.2102 & 0.0304
\end{bmatrix}
\]

Figure 3-13: Fritchman's state diagram and matrix of transition probabilities for a 30° satellite pass

For the rest of the elevation angle passes, the error-free run distribution is described by two exponential terms. Table 3-7 lists the parameters obtained through curve-fitting procedure.
Table 3-7: Coefficients through curve-fitting procedure for a range of elevation angles

<table>
<thead>
<tr>
<th>ELEVATION ANGLE</th>
<th>A_1</th>
<th>a_1</th>
<th>A_2</th>
<th>a_2</th>
<th>A_3</th>
<th>a_3</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>0.2</td>
<td>-0.001</td>
<td>0.52</td>
<td>-0.007</td>
<td>0.24</td>
<td>-0.08</td>
</tr>
<tr>
<td>23°</td>
<td>0.78</td>
<td>-0.0013</td>
<td>0.1246</td>
<td>-0.00007</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>30°</td>
<td>0.53</td>
<td>-0.0011</td>
<td>0.23</td>
<td>-0.00015</td>
<td>0.23</td>
<td>-0.09</td>
</tr>
<tr>
<td>40°</td>
<td>0.25</td>
<td>-0.0005</td>
<td>0.3</td>
<td>-0.00005</td>
<td>0.45</td>
<td>-0.07</td>
</tr>
<tr>
<td>52°</td>
<td>0.66</td>
<td>-0.03</td>
<td>0.3</td>
<td>-0.005</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>63°</td>
<td>0.49</td>
<td>-0.0005</td>
<td>0.27</td>
<td>-0.00004</td>
<td>0.23</td>
<td>-0.08</td>
</tr>
<tr>
<td>68°</td>
<td>0.1</td>
<td>-0.001</td>
<td>0.37</td>
<td>-0.05</td>
<td>0.52</td>
<td>-0.007</td>
</tr>
<tr>
<td>74°</td>
<td>0.77</td>
<td>-0.22</td>
<td>0.18</td>
<td>-0.023</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 3-8 below lists the transition probabilities obtained from the sets of measured data for a range of elevation angles. These transition probabilities have calculated based on Equation 3-9.

Table 3-8: Fritchman model transition probabilities for a range of elevation angles

<table>
<thead>
<tr>
<th>Elev.</th>
<th>P_{11}</th>
<th>P_{13}</th>
<th>P_{22}</th>
<th>P_{24}</th>
<th>P_{33}</th>
<th>P_{24}</th>
<th>P_{41}</th>
<th>P_{42}</th>
<th>P_{43}</th>
<th>P_{44}</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>0.9990</td>
<td>0.0010</td>
<td>0.9930</td>
<td>0.00698</td>
<td>0.9231</td>
<td>0.0769</td>
<td>0.1998</td>
<td>0.5164</td>
<td>0.2215</td>
<td>0.0623</td>
</tr>
<tr>
<td>30°</td>
<td>0.9989</td>
<td>0.0011</td>
<td>0.9999</td>
<td>0.00001</td>
<td>0.9139</td>
<td>0.0861</td>
<td>0.5294</td>
<td>0.2299</td>
<td>0.2102</td>
<td>0.0304</td>
</tr>
<tr>
<td>40°</td>
<td>0.9995</td>
<td>0.0005</td>
<td>0.9995</td>
<td>0.00005</td>
<td>0.9329</td>
<td>0.0677</td>
<td>0.2499</td>
<td>0.2999</td>
<td>0.4196</td>
<td>0.0305</td>
</tr>
<tr>
<td>63°</td>
<td>0.9995</td>
<td>0.0005</td>
<td>0.9999</td>
<td>0.00004</td>
<td>0.9231</td>
<td>0.0769</td>
<td>0.4898</td>
<td>0.2699</td>
<td>0.2123</td>
<td>0.0279</td>
</tr>
<tr>
<td>68°</td>
<td>0.9990</td>
<td>0.001</td>
<td>0.9512</td>
<td>0.0488</td>
<td>0.9930</td>
<td>0.0069</td>
<td>0.0999</td>
<td>0.3519</td>
<td>0.5163</td>
<td>0.0318</td>
</tr>
</tbody>
</table>

Graph 3-17a: Experimental burst interval for a satellite pass of maximum elevation angle of 62°.

Graph 3-17b: Experimental burst interval for a satellite pass of maximum elevation angle of 74°.
From previous research, the error-burst length distributions obtained from recorded error sequences show that the Markov chain consisting of a unique error state is sufficient to accurately describe the digital channel. Hence, the error burst length distribution from Equation (3-7) can be written as

\[ P(1^m|0) = \alpha_N \beta_N^m \]  

(3-18)

Expressed using a logarithmic form, the error burst length distribution becomes a straight line.

\[ f_i(m) = \log_{10} P(1^m|0) \]

\[ f_i(m) = a_N + mb_N \]  

(3-19)

where \( a_N = \log_{10} \alpha_N \) and \( b_N = \log_{10} \beta_N \)

The experimental error-burst length distribution for a satellite pass of 62° and 74° are shown in Graphs 3-17a and 3-17b. The error-burst lengths are not plotted for the lower elevation angles of up to 52° as there were too few samples and the lengths were 1 to 2 bits. From the graphs, the error burst length distribution does not seem to follow a straight line. Therefore, it is suspected that a single error state is not sufficient to describe the distribution of errors for these higher elevation angles.

### 3.8.2. UHF Digital Channel Simulator

From the estimated Fritchman's model parameters, an error sequence simulator has been realized as shown in Figure 3-12. The implementation of the digital channel simulator is simple and requires only a uniform random number generator and the estimated parameter values, \( \alpha_i \) and \( \beta_i \). The program determines the transition probabilities between the Markov chain states from the estimated model parameters. Using the above Fritchman model parameters, the error sequences were then generated for all elevation angles.

From the set of transition probabilities \( P_{ij} \), one can compute the \( a priori \) probabilities \( P_i \), and thus determine the state at the beginning of the error sequence. The relationship between the transition probabilities and the \( a priori \) probabilities is given by:

\[ P_i = P_i P_{ij} + P_j P_{N,j} \quad i = 1, \cdots, k \]

\[ \sum_{i=1}^{N} P_i = 1 \]  

(3-20)

This set of \( N \) equations and \( N \) unknowns is easily resolved by linear algebra.
Graphs 3-18a to 3-18f show the interval length distribution $P(0^m/1)$ calculated from each 5,000,000 bits long error sequence generated with the digital channel simulator.
As expected, a good fit between the Fritchman's model curve and the actual interval length distribution is obtained for all elevation angles considered. For further analysis and comparison, these generated error sequences have been analysed in terms of burst lengths and burst gaps and their corresponding cumulative histograms are compared with the experimental cumulative histograms as follows.
The following graphs depict the cumulative burst histograms for a range of satellite elevation passes from 23° to 74°. It is observed from the graphs that the generated burst lengths produced from the digital channel simulator are a close fit to the measured burst lengths.
From the plots of the gap cumulative histograms, it is observed that the generated gaps fit well with the experimental gaps for all elevation angles.

The graphs of cumulative gap histograms for a range of satellite elevation passes.
3.8.3. Discussions on the Fritchman model

From all results obtained thus far, it is deduced that the proposed UHF digital channel simulator is able to predict the observed error sequences of the channel accurately. This is verified through the plots of interval lengths distributions for satellite passes at 23° to 74°, cumulative histograms of burst lengths and burst gaps and comparisons with the measured data.

However, as explained further in Chapter 5, when the Fritchman model is evaluated in terms of error control performance, the results obtained are different to what is anticipated, especially when considering the effects of interference. It is suspected that the error burst distribution is a function of at least two exponential terms and therefore, two error states for the higher elevation angles. Therefore, we propose to investigate a 4-state Markov model, consisting of two good states and two bad states, to represent the intervals between the bursts and the bursts correspondingly.
3.9. The 4-State Markov Model

The 4-state Markov model is shown below. States 1 and 2 correspond to the error (bad) states with state 1 representing the shorter burst lengths and state 2 representing the longer burst lengths. Correspondingly, states 3 and 4 will generate the good bits, with varying means in the gap lengths and representing the short gaps and longer gaps respectively.

![Four-state probabilistic Markov model diagram](image)

The steady-state equations for the four-state Markov model are as follows:

\[
\begin{align*}
P_1 &= P_1 (P_{13} + P_{14}) = P_3 P_{31} + P_4 P_{41} \\
P_2 &= P_2 (P_{23} + P_{24}) = P_3 P_{32} + P_4 P_{42} \\
P_3 &= P_3 (P_{31} + P_{32}) = P_1 P_{13} + P_2 P_{23} \\
P_4 &= P_4 (P_{41} + P_{42}) = P_1 P_{14} + P_2 P_{24}
\end{align*}
\]

\[P_1 + P_2 + P_3 + P_4 = 1\]  \hspace{1cm} (3-21)

\[P_1 P_{11} + P_3 P_{31} + P_4 P_{41} = P_1\]  \hspace{1cm} (3-22)

\[P_2 P_{22} + P_3 P_{32} + P_4 P_{42} = P_2\]  \hspace{1cm} (3-23)

The method of moments was used to decompose the mixture of the exponential distributions for the error bursts and gaps. Many methods have been devised and used for estimating the parameters of mixture distributions, ranging from Pearson’s method of moments, through formal maximum likelihood approaches, to informal graphical techniques.

Rider has applied the method of moments to the decomposition of a mixture of two exponential distributions [Rider61]:

\[f(x) = p \frac{1}{\mu_1} \exp(-x/\mu_1) + (1 - p) \frac{1}{\mu_2} \exp(-x/\mu_2)\]  \hspace{1cm} (3-24)
Chapter 3: LEO Channel Measurements and Channel Characterisation

From the above, we can write the 0th, 1st, 2nd and 3rd moments about zeros as

\[ 1 = p + (1 - p) \]
\[ \bar{x} = p \mu_1 + (1 - p) \mu_2 \]
\[ \frac{m_2}{2} = p \mu_1^2 + (1 - p) \mu_2^2 \]
\[ \frac{m_3}{6} = p \mu_1^3 + (1 - p) \mu_2^3 \]

(3-25a-d)

and for convenience we set

\[ 1 = T_0 \quad \bar{x} = T_1 \quad \frac{m_2}{2} = T_2 \quad \frac{m_3}{6} = T_3 \]

(3-26)

Now, multiplying (3-25a) by some constant \( \alpha_2 \), the (3.25b) by \( \alpha_1 \), and the third by -1, and adding we obtain

\[ p\left(-\mu_1^2 + \alpha_1 \mu_1 + \alpha_2\right) + (1 - p)\left(-\mu_2^2 + \alpha_1 \mu_2 + \alpha_1\right) = \alpha_2 T_0 + \alpha_1 T_1 - T_2 \]

(3-26)

Similarly, if we multiply 2nd (3-25b) by some constant \( \alpha_2 \), the (3-25c 3rd ) by \( \alpha_1 \), and the last by -1, and adding we obtain

\[ p\left(-\mu_1^3 + \alpha_1 \mu_1^2 + \alpha_2 \mu_1\right) + (1 - p)\left(-\mu_2^3 + \alpha_1 \mu_2^2 + \alpha_2 \mu_2\right) = \alpha_2 T_1 + \alpha_1 T_2 - T_3 \]

(3-27)

Thus, if we choose \( \alpha_1 \) and \( \alpha_2 \) such that \( \mu_1 \) and \( \mu_2 \) are the roots of \( \mu^2 - \alpha_1 \mu - \alpha_2 = 0 \), we obtain:

\[ \alpha_2 T_0 + \alpha_1 T_1 = T_2 \]
\[ \alpha_1 T_1 + \alpha_1 T_2 = T_3 \]

(3-28)

from which:

\[ \alpha_1 = \frac{\left(T_1 T_2 - T_0 T_3\right)\left(T_1 T_2 - T_0 T_3\right)}{\left(T_1^2 - T_0 T_2\right)} \]
\[ \alpha_2 = \frac{\left(T_1 T_3 - T_2 T_3\right)\left(T_1 T_2 - T_0 T_2\right)}{\left(T_1^2 - T_0 T_2\right)} \]

(3-29)

Thus, we estimate the \( \alpha \) from (3.4) using the observed \( T_i \) values, and then we estimate the \( \mu \) from

\[ \mu_1, \mu_2 = \frac{\alpha_1}{2} + \frac{1}{2} \left(\alpha_1^2 + 4\alpha_2\right)^{1/2} \]

(3-30)

From \( \hat{\mu}_1 \) and \( \hat{\mu}_2 \) and Equation (3-25b) we can estimate \( \hat{\rho} \).

The measured error sequences were analysed in terms of the means of burst lengths and burst gaps using the above mentioned method of moments. The transition probabilities of the four-state model can therefore be calculated by solving Equations (3-21) and (3-22). The results shown here are calculated for a selected threshold density of 0.2 and for probability of errors in a bad state of 0.4. The probability of errors has been chosen through a quick estimation by eye of the burst regions of the data.
The error sequences were then generated using the above transition probabilities in Table 3-8 and the comparisons of the generated data with the experimental data are shown in Table 3-9. Each data sample is of length 50,000,000 bits.

<table>
<thead>
<tr>
<th>ELEVATION ANGLE</th>
<th>P_{13}</th>
<th>P_{14}</th>
<th>P_{23}</th>
<th>P_{24}</th>
<th>P_{31}</th>
<th>P_{32}</th>
<th>P_{41}</th>
<th>P_{42}</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>0.62</td>
<td>0.039</td>
<td>0.054</td>
<td>0.002</td>
<td>0.008</td>
<td>5.5e-5</td>
<td>2.4e-4</td>
<td>2.3e-5</td>
</tr>
<tr>
<td>23°</td>
<td>0.75</td>
<td>0.0065</td>
<td>0.0268</td>
<td>0.0005</td>
<td>0.0023</td>
<td>0.5e-5</td>
<td>2.0e-5</td>
<td>3.0e-6</td>
</tr>
<tr>
<td>30°</td>
<td>0.65</td>
<td>0.041</td>
<td>0.0208</td>
<td>0.0038</td>
<td>1.65e-3</td>
<td>3.8181e-5</td>
<td>8.6e-5</td>
<td>1.4545e-5</td>
</tr>
<tr>
<td>40°</td>
<td>0.624</td>
<td>0.0093</td>
<td>0.027</td>
<td>0.04</td>
<td>6.3e-4</td>
<td>7.073e-5</td>
<td>1.791e-5</td>
<td>2.091e-6</td>
</tr>
<tr>
<td>52°</td>
<td>0.3</td>
<td>0.02</td>
<td>0.045</td>
<td>1.0e-3</td>
<td>0.027</td>
<td>8.1e-5</td>
<td>0.0011</td>
<td>6.9e-5</td>
</tr>
<tr>
<td>63°</td>
<td>0.605</td>
<td>0.0257</td>
<td>2.4e-4</td>
<td>3.0e-6</td>
<td>0.05</td>
<td>8.1e-5</td>
<td>1.5e-3</td>
<td>5.0e-5</td>
</tr>
<tr>
<td>74°</td>
<td>0.78</td>
<td>0.013</td>
<td>2.0e-4</td>
<td>1.0e-5</td>
<td>0.3</td>
<td>4.0e-5</td>
<td>0.0022</td>
<td>5.0e-5</td>
</tr>
</tbody>
</table>

Table 3-9: Transition probabilities for the 4-state model for a range of elevation angles

<table>
<thead>
<tr>
<th>ELEVATION ANGLE</th>
<th>MEAN BURST1</th>
<th>MEAN BURST2</th>
<th>PROB BURST1</th>
<th>MEAN GAP1</th>
<th>MEAN GAP2</th>
<th>PROB GAP1</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>1.5171</td>
<td>27.3257</td>
<td>0.9969</td>
<td>266.2971</td>
<td>380.36</td>
<td>0.9787</td>
</tr>
<tr>
<td>real data</td>
<td>1.5083</td>
<td>25.7614</td>
<td>0.9932</td>
<td>273.9906</td>
<td>377.277</td>
<td>0.8889</td>
</tr>
<tr>
<td>generated</td>
<td>1.3236</td>
<td>57.6811</td>
<td>0.9994</td>
<td>901.516</td>
<td>383.26</td>
<td>0.9715</td>
</tr>
<tr>
<td>23°</td>
<td>1.3002</td>
<td>59.5538</td>
<td>0.9944</td>
<td>897.835</td>
<td>397.66</td>
<td>0.9781</td>
</tr>
<tr>
<td>real data</td>
<td>1.3939</td>
<td>48.1715</td>
<td>0.9999</td>
<td>1562.7</td>
<td>1079.2</td>
<td>0.9170</td>
</tr>
<tr>
<td>generated</td>
<td>1.5571</td>
<td>47.4333</td>
<td>0.9564</td>
<td>1491.2</td>
<td>1012.1</td>
<td>0.9083</td>
</tr>
<tr>
<td>30°</td>
<td>1.6212</td>
<td>81.9278</td>
<td>0.9999</td>
<td>2617.5</td>
<td>432.56</td>
<td>0.7855</td>
</tr>
<tr>
<td>real data</td>
<td>2.0815</td>
<td>11.6446</td>
<td>0.9572</td>
<td>2534.4</td>
<td>423.01</td>
<td>0.8389</td>
</tr>
<tr>
<td>generated</td>
<td>1.7081</td>
<td>44.301</td>
<td>0.9959</td>
<td>98.824</td>
<td>935.68</td>
<td>0.9896</td>
</tr>
<tr>
<td>40°</td>
<td>3.3106</td>
<td>48.3148</td>
<td>0.9950</td>
<td>74.78</td>
<td>874.145</td>
<td>0.9134</td>
</tr>
<tr>
<td>real data</td>
<td>1.3817</td>
<td>230.27</td>
<td>0.9994</td>
<td>54.9535</td>
<td>673.6289</td>
<td>0.9869</td>
</tr>
<tr>
<td>generated</td>
<td>16.398</td>
<td>203.07</td>
<td>0.9970</td>
<td>53.43</td>
<td>689.2143</td>
<td>0.9206</td>
</tr>
<tr>
<td>52°</td>
<td>1.1</td>
<td>1971.5</td>
<td>0.9999</td>
<td>41.353</td>
<td>468.334</td>
<td>0.9982</td>
</tr>
<tr>
<td>real data</td>
<td>9.169</td>
<td>19804</td>
<td>0.9987</td>
<td>15.6207</td>
<td>448.9332</td>
<td>0.9313</td>
</tr>
</tbody>
</table>

Table 3-10: Comparisons of statistics between the experimental data and 4-state model for a range of elevation angles

From 15° to 40°, the means in burst lengths and burst gaps of the generated data are very close to the experimental data and within approximately 5% of the original values. At 52°, the accuracy deteriorates; however, a reasonable result is still obtained. Beyond this range of elevation angles, at 63° and above, it has been rather difficult to achieve a good fit with the means of the short burst length while all other values of the means in longer bursts and gaps are within 10% of their original values. At elevation angles above 63°, it is noticeably obvious that the error bursts occur in clusters and are not random.
Chapter 3: LEO Channel Measurements and Channel Characterisation

The graphs above depict the plots of cumulative histograms for a range of elevation angles.

Graph 3-21a: Burst cumulative histogram for a 23° pass

Graph 3-21b: Burst cumulative histogram for a 30° pass

Graph 3-21c: Burst cumulative histogram for a 40° pass

Graph 3-21d: Burst cumulative histogram for a 52° pass

Graph 3-21e: Burst cumulative histogram for a 62° pass

Graph 3-21f: Burst cumulative histogram for a 74° pass
The plots above depict the gap cumulative histograms for a range of satellite elevation angles. We can conclude that up to 52°, the four-state Markov model can accurately model and predict the measured
error sequences to about 5% of its experimental values. Beyond this range of elevation angles, as the error bursts occur in clusters and the four-state probabilistic model generates randomly distributed bursts, the model can only provide a reasonable approximation to the values.

The comparisons between the modelling accuracy of the multiple state Fritchman model and the four-state model are shown in the previous plots of cumulative histograms. From 15 to 63°, the Fritchman model is able to model more precisely the distribution of the experimental bursts and gaps than the four-state model. However, at satellite passes above 63°, the four-state model is much better than the Fritchman model in that, it takes into account the error bursts as a function of two exponentials. Therefore, it can model more accurately the distribution of the two types of bursts, the short bursts and the longer bursts.

3.10. Conclusion

This chapter has presented a literature review of the various types of fading channels for different environments and the types of modelling used to characterise these channels. Specifically, this chapter describes the LEO UHF measurement campaign which was conducted at the University of Surrey and presents the results of the error sequences of the LEO satellite channel for the first time. The research has investigated various generative models in the attempt to characterise these error sequences for a broad range of elevation angles. It is found that the two-state Gilbert model cannot describe such sequences. The Fritchman one-error state model can accurately model the error sequences up to 63°, and more precisely than the four-state model. However, from elevation angles above 63°, the four-state model is able to predict the error sequences more accurately.
3.11. References


Chapter 3: LEO Channel Measurements and Channel Characterisation


Chapter 4
The Data Link Layer - Protocol Design Issues And
Error Control Techniques

4.1. Introduction
The first computer system to employ radio as a medium for sending and receiving computer data was the ALOHA system at the University of Hawaii. The engineers experimented with data in short self-contained informational bursts called packets in a network as an alternative means to point-to-point wires. This was because telephone lines were expensive and unreliable, and it was not necessary for computers to communicate with one another on a continual basis. The system first went on air in 1971 and has become the ancestor of all packet broadcasting systems.

Much was learned about packet radio from the early experimental research efforts. However, it was not until the widespread advent of the personal computer that packet radio was really considered by a handful of forward thinking radio amateurs as a serious means of communications. Subsequently, radio amateurs (ham operators) in the U.S., Canada and Japan have agreed on a standardised protocol, which eventually lead to the development of the AX.25 protocol.
This chapter provides an introduction to the collection of protocols called the ‘PAC SAT’ protocol suite. This was developed for the SSTL store-and-forward LEO microsatellites which operate at a higher protocol layer than the AX.25 protocol.

Of particular interest is the point-to-multipoint Broadcast Protocol (PBP) which is a component of PAC SAT protocol suite which adopts the Selective Repeat (SR) protocol. In the following sections, the implementation of the sliding-window SR protocol in the OPtimised Network Engineering Tool (OPNET) is reviewed. The SR protocol developed in OPNET represents a typical scenario of the PACS AT Broadcast Protocol (PBP) with slight modifications and functions as a platform to simulate various hybrid-ARQ schemes. It is necessary to conduct simulations to obtain reliable estimates of protocol performance. OPNET was selected as a simulation tool as it supports hierarchical object-based modelling and C-type applications. Each specific function of each protocol from the physical, data link to network layer is described. The underlying mechanisms of the SR protocol are illustrated through a Finite State Machine (FSM) diagram for ease of explanation. Protocol design issues such as buffering requirements, the size of the sending and receiving windows, and packet timeouts will be dealt with.

The suitability of error control techniques for the existing system is investigated in this chapter. Much research has been performed in the field of error control coding since Shannon wrote his 1948 paper on communications theory, which completely revolutionised the coding field [Shannon48]. Shannon showed that it was possible by coding to obtain reliable communications at the channel capacity with values of $E_b/N_0$ as low as -1.6dB.

A search of the literature has found little in the public domain regarding coding schemes used or proposed for LEO satellite communications. Globalstar has proposed a $\frac{1}{2}$-rate constraint length 9, convolutional encoder with Viterbi decoding and interleaving techniques, while the Iridium-66 constellation employs a $\frac{1}{5}$-rate convolutional code with Viterbi decoding [Maine95]. Both Globalstar and Iridium are classified as Big LEO constellations and are intended to provide voice, data, paging and fax services. The ECO-8 equatorial little-LEO constellation uses $\frac{1}{2}$ and $\frac{1}{4}$-rate convolutional schemes for voice and data respectively [ECO-8]. For the rest of the LEO constellations, no public information regarding the error control techniques has been found.

As there is little knowledge of the LEO channel conditions, it is not a trivial task to design suitable error correction schemes to combat the errors in the channel. In random-error channels such as the deep space channel, noise affects signals independently. However, for channels with memory, the noise is not independent from transmission to transmission, i.e. bursts of errors are produced due to the effects of signal fading. From chapter 3, it is found that the LEO channel exhibits compound errors, a mixture of bursty and random errors as exhibited in many real communications channels.

This chapter compares two error-control techniques, namely Forward Error Correction (FEC) and Automatic Retransmission reQuest (ARQ), and proposes a hybrid-ARQ scheme as an alternative solution for optimising data throughput in the LEO channel. A comprehensive literature survey has
Chapter 4: The Data Link Layer - protocol design issues and error control techniques

therefore been performed on existing hybrid-ARQ techniques. It has identified suitable hybrid schemes and coding techniques to be investigated in the link.

4.2. The PACSAT protocol suite

The PACSAT protocol suite was developed for the SSTL store-and-forward satellite communication system and the protocol definitions were previously published [Ward93, Price89a,b]. This protocol suite is implemented in several layers but does not strictly adhere to the recommended seven-layer Open Systems Interconnection (OSI) system. At the highest layer, all messages are encapsulated in a standard envelope called the PACSAT file header. All other protocols function above the AX.25 amateur packet radio link-layer protocol. We focus mainly on the PACSAT Broadcast protocol as follows.

4.2.1. PACSAT Broadcast Protocol

PACSAT Broadcast Protocol (PBP) is one of the protocols developed as a component of the PACSAT protocol suite. It is a point-to-multipoint protocol dedicated for transferring directories and messages from the satellite to ground stations on the downlink communications channel, which acts as a natural broadcast channel.

PBP uses datagrams. A datagram is a block of data that is either delivered correctly by the data link protocol, or lost completely. If a datagram is lost, the data link protocol does not notify the higher-layer processes. It is solely the function of the higher-layer protocols to perform error control, to detect the missing datagrams and to replace them. The operation of PBP is illustrated in Figure 4-2. Before transmission, a message is initially segmented into a small number of data packets, each of which is broadcast on the downlink. All the stations which reside in the satellite's footprint are able to receive these messages.

The PBP protocol first places its block of data inside the 'data' field of an AX.25 frame and transmits it. At the receiver, the receiving AX.25 process checks the frame for errors and passes the error-free frames up to the receiving PBP process. Any packets that are corrupted are discarded. Each error-free
message packet is then reassembled into its corresponding location as in the original message. These packets are not individually acknowledged by each receiving station.

![Send File as Packets](image)

![Send Missing Packets](image)

**Figure 4-2: PACSAT Broadcast hole-filling**

Missing packets leave holes in the message and it is necessary for the ground terminal to send a hole fill request to the satellite. Only the packets which specifically fill the holes in the messages are sent by the satellites. In effect, this procedure implements an ideal selective repeat request protocol; only the packets actually missed by the ground terminal are retransmitted by the satellite, yet the satellite station does not have to stop and wait for an acknowledgment from every station for every packet. The main elements of the PBP server datagram are illustrated in Figure 4-3.

<table>
<thead>
<tr>
<th>Flags</th>
<th>File ID</th>
<th>File Type</th>
<th>Data Offset</th>
<th>Data</th>
<th>Frame Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>0-244</td>
<td>2</td>
</tr>
</tbody>
</table>

**Figure 4-3: PBP server datagram in bytes [not to scale]**

The eight flags bits are used to differentiate different datagram types, protocol version numbers, etc. The file identification number identifies the file. Data offset indicates the offset from the beginning of the file at which client should place the data contained in the datagram. The file type tells what type of message body this message contains. Using this byte, PBP clients can ignore datagrams from messages that they are not interested in. The frame check is a Cyclic Redundancy Check (CRC) of two bytes in the frame. Altogether, these provide an overhead of just under 5%. Clients transmit their request to the PBP server using the request datagram in Figure 4-4.

<table>
<thead>
<tr>
<th>Flags</th>
<th>File Serial</th>
<th>Block Size</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>1</td>
<td>0-234</td>
</tr>
</tbody>
</table>

**Figure 4-4: PBP client datagram format in bytes [not to scale]**
Two of the flag bits identify four possible command types. File identification number indicates which file the client is referring to, and block size tells the server how many data bytes to put in each datagram when fulfilling the request. The data portion of the client datagram contains selective repeat requests.

### 4.2.2. AX.25 Data Link Layer Protocol

This synchronous data protocol used in the Amateur Radio service is a derivative of the CCITT X.25 layer 2 protocol. It follows, in principle, the X.25 Recommendation with the exception of an extended address field and the addition of the Unnumbered Information (UI) frame. X.25 is based upon the IBM Synchronous Data Link Control protocol (SDLC), from which are derived Link Access Procedure B (LAPB) and High Level Data Link Control (HDLC). These synchronous protocols operate over any physical layer protocol that provide a bit stream. The AX.25 protocol will work equally well in either half- or full-duplex Amateur Radio environments. The structure of the AX.25 frame is described as follows [AX25spec].

<table>
<thead>
<tr>
<th>Flag</th>
<th>Source</th>
<th>Destination</th>
<th>Control</th>
<th>ID</th>
<th>Data</th>
<th>FCS</th>
<th>Flag</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>8</td>
<td>1</td>
<td>1</td>
<td>0-256</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 4-5: AX.25 frame structure in bytes [not to scale]

Link-layer packet radio transmissions are sent in small block of data called frames. The flag field denotes the start and end of a frame. It consists of a zero followed by six ones, followed by another zero, or 01111110 and this sequence is not allowed to occur anywhere else inside a complete frame. The address (source and destination) field is used to identify both the source of the frame and its destination.

The control field identifies the type of frame being sent, and conveys commands and responses from one end of the link to the other in order to maintain proper link control. There are three general types of AX.25 frames; they are namely the Information frame (I frame), the Supervisory frame (S frame), and the Unnumbered frame (U frame). The protocol identifier (PID) field identifies what kind of layer-3 protocol, if any, is in use while the information field (data) is used to convey user data.

The FCS is calculated by both the sender and receiver of a frame. It is calculated in accordance with ISO 3309 (HDLC) Recommendations. The CRC error detection code employed in AX.25 is a 16-bit cyclic redundancy check with the CCITT generator polynomial of \(X^{16} + X^{15} + X^2 + 1\). It is basically an expurgated (32767, 32751) Hamming code of minimum distance 4. The code will detect all errors of weight 3 or less, all odd weight errors, all bursts of length 16 or less, 99.997 percent of bursts of length 17 and 99.9985 percent of bursts of length 18 or more. Experiments have indicated that the link between the Terminal Node Control (TNC) which assembles the packets and the user’s personal computer may be prone to errors caused by a lack of flow control. Therefore, another CRC, also 16 bits was used to provide error protection to the broadcast frame as well.
4.3. **Improvements to current protocol**

AX.25 was developed in the early 1980's. Although it has become the universal standard link-level protocol for amateur packet radio, it is widely recognised as being far from optimal and performs poorly on non-benign channels.

To a certain extent, the effects of increasing packet error rates (PER) can be reduced by decreasing the sizes of the frame. As the frame length decreases, the probability of burst errors in a frame is reduced. This strategy is limited as frame headers must be included with each frame. Assuming a fixed amount of header to be included, the header overhead increases as the frame length decreases. A combination of header size, link BER and amount of data, thus determines the optimum throughput for any system.

The source and destination address fields of the AX.25 protocol consume 16 bytes. Due to the nature of the satellite orbit, the satellite is only accessible to groundstations within its footprint during a pass. Clearly, the allocated bytes are more than sufficient to support a network of users. Such overhead can be allocated to compensate for the amount of redundancy generated by FEC codes.

The errors within the frames can be corrected by a Forward Error Correction (FEC) code, up to a point. The quality of delivered data will eventually degrade at high levels of noise in all pure FEC schemes. Therefore FEC alone is not suitable for communications over links that exhibit highly variable bit error rates. For such channels, such as the LEO satellite channel, the incorporation of a hybrid-ARQ technique, which is a combination of FEC and ARQ, seems most promising. Various hybrid-ARQ schemes are therefore reviewed.

4.4. **Hybrid-ARQ schemes**

A hybrid-ARQ scheme is a combination of FEC and ARQ. In an FEC system, redundancy is inserted into the original data stream and the noise-corrupted data is recovered at the receiver through error correction techniques. The principal of FEC is to get it right the very first time. However, this technique does not guarantee a hundred percent error-free (reliable) data delivery. In contrast, in ARQ, a high-rate error-detecting code, say an \((n,k)\) linear block code incorporated with a certain retransmission protocol is used. At the receiver, erroneous packets are discarded and retransmission requests are made using a feedback channel.

Three basic types of ARQ systems are Stop-and-Wait (SW), Go-Back-N (GBN) and Selective Repeat (SR). The SW protocol is inefficient due the idle time spent waiting for an ACK to arrive before transmitting the next frame. In GBN, whenever a received frame is detected in error, next \(N-1\) received frames are rejected even though they may be error-free. This results in severe deterioration of throughput performance if a large round-trip delay is involved. Therefore, GBN is ineffective for systems with high data rates and large round-trip delays due to unnecessary retransmission. In SR, only the negatively acknowledged codewords are re-sent. This provides a significantly higher throughput than GBN during higher error rates, but requires sufficient receiver buffer storage and more complex...
logic to avoid buffer overflow. In a SR system, the transmitter must keep a buffer of what it has sent so that retransmission is possible. The receiver may store unreliable frames and combine them with subsequent retransmission to improve reliability. With ARQ, every frame transmitted must be stored long enough for it to be received, processed and (if necessary) for a repeat request to be received and processed. So, the buffer size on-board the spacecraft needs to be large enough to store all data transmitted in that amount of time.

The performance of an ARQ system is usually measured in terms of its reliability and throughput. In a pure ARQ system, the probability of undetected errors can be made very small, by proper choice of error-detecting codes. Therefore, the reliability of the system is very high. ARQ protocols provide higher levels of reliability than their FEC counterparts because codes can detect at least twice as many errors as they can correct. This increase in reliability is provided at the expense of a reduction in throughput caused by retransmissions.

The throughput of an ARQ system is defined as the average number of encoded data packets accepted by the receiver in the time it takes the transmitter to send a single k-bit data packet. The ARQ technique is adaptive in the sense that retransmissions are requested when the errors occurs. However, the throughput of the ARQ system is dependent on the number of retransmissions and hence the channel conditions. During high levels of noise, too frequent retransmissions will result in a significant reduction in throughput performance. Since no retransmissions are required in an FEC system, the throughput of the system is constant, and it is equal to the rate of the code used by the system.

The efficiency of a link utilising the SW protocol is

$$\eta_{SW} = \frac{1 - P}{N}$$

(4-1)

where \(N\) is the number of messages contained in the interval between the start of a message and the start of the next (or a repeat), \(P\) is the probability of message error and a \((n,k)\) code is used for error detection.

For a GBN-based system,

$$\eta_{GB} = \frac{1 - P}{1 + (n - 1)P}$$

(4-2)

Whilst, the efficiency of SR-ARQ is just the probability of message reception multiplied by the rate of the coding.

$$\eta_{SW} = (1 - P)\frac{k}{n}$$

(4-3)

Taking into account the advantages and disadvantages of both ARQ and FEC, a combination of FEC for the most frequent error patterns, with error detection and retransmission for the less likely error patterns, is more efficient than ARQ alone.
4.4.1. Type-I hybrids

A type-I hybrid uses a code designed for simultaneous error detection and correction. When a received word is detected in error, the receiver first attempts to correct the errors, within its error-correcting capability. If an uncorrectable error pattern occurs, the receiver rejects the received word and requests for a retransmission of the same codeword. This process is repeated until the codeword is either successfully received or successfully decoded. At low bit error rates, the throughput of the type-I hybrid is less than its corresponding ARQ system, but higher at high channel error rates as its error-correction capability reduces the frequency of retransmission.

Type-I schemes are best suited for communication systems in which a fairly constant level of noise that experience occasional bursts and interference is anticipated on the channel [Lin84]. Type-I schemes offer better throughput than their type-II contemporaries during these conditions. When the noise level increases for a period of time exceeding a single packet length, the type-I protocol’s only course of action is to continually retransmit, which will result in significant throughput reduction.

To handle this problem, the type-I hybrid can be modified to monitor retransmission statistics and change code rate accordingly, which was proposed for a slowly varying channel [Wicker7,8]. Alternatively, multiple received packets can be combined to create a more reliable version of the transmitted data, through combining techniques.

As the type-I hybrid is only suited for channels with constant levels of noise, it will not be considered further.

4.4.2. Type-II hybrids

Metzner first proposed the type-II hybrid [Metzner2,3]. His scheme was later extended and modified by many others [Lin2,Wang83,Krishna87,Bennelli1]. For this system, a message in its first transmission is coded with parity-check bits for error detection. When the receiver detects the presence of errors, it saves the erroneous word in a buffer, and at the same time requests a retransmission. The retransmission consists of a block of parity-check bits used to correct the errors in the erroneous word stored in the receiver buffer. If error correction is unsuccessful, the receiver then requests for a second retransmission. This second retransmission may either be a repetition of the original codeword or another block of parity-check bits. The throughput of the type-II hybrid is the same as that of a pure ARQ system in event of high error rates. When the channel is more noisy, its throughput is even higher than the corresponding pure ARQ system.

For a type-I hybrid, since parity bits for error correction are sent with every packet, the code rate places an upper limit on the throughput efficiency of the system. For a type-II system, since parity bits for error detection only are sent on the first transmission, the upper limit on throughput efficiency is near 1.

In other words, parity bits for error correction are transmitted only when they are needed. It is this feature which gives the parity retransmission strategy the ability to adapt to changing channel conditions. When the channel is quiet, parity bits for error detection only are transmitted, and a high
throughput is maintained. Only when noise or interference cause packets to be received incorrectly are parity bits for error correction transmitted, resulting in a reduced throughput.

### 4.4.3. Code Combining

In event of uncorrectable errors, which exceed the error-correcting capability of a given code, it is possible to combine multiple repeats of the same packet to obtain a more powerful lower rate code which enables the packets to be decoded successfully. Code combining has been thoroughly examined by Chase [Chase1]. The code combining technique involves taking \( N \) packets encoded at rate \( R \) and creating a single packet encoded at rate \( R/N \). Therefore, combining is done at the codeword level and not at the bit or symbol level. Code combining is ideally suited for packet communications and also designed to work over very noisy channels where an arbitrary number of noisy packets may be combined [Chase1].

Code combining has been applied to ARQ strategies [Chase2,3,Kalle13,4,5,Hagl,2].

### 4.4.4. Diversity Combining

In diversity combining, multiple copies of a packet encoded at rate \( R \) are combined bit by bit to create a single codeword from the original rate \( R \) code. Thus, each bit in the resulting packet is made more reliable through the receipt of multiple copies of each bit. The combining of the individual bit can be performed using either soft or hard decision techniques. The use of diversity combining with either Viterbi or majority-logic decoding are found in the literature [Wicker10].
4.5. Type-II hybrid based on punctured RS codes

In the selection of a suitable error control code, among the principal design criteria that must be satisfied are the code must be able to (substantially) improve the data throughput of the system while maintaining high reliability of data. Taking into account bandwidth constraints, the amount of redundancy should be minimised due to the limited bandwidth available. As the LEO communications channel is shown to exhibit varying degrees of burstiness for a wide range of elevation angles, the coding scheme has to show flexibility to cope with the range of possible conditions, hence adaptivity. With regards to the SSTL system, it should be suitable for packet communications at data rates of 9.6kbit/s and adaptable to the varying packet lengths. Finally, in terms of implementation, the code has to provide a cost-effective solution, the hardware should be simple so as to minimise cost. Further consideration lies in whether the codec is available commercially or needs to be developed specifically.

RS codes were first described by Reed and Solomon in 1960 and are a special subclass of the Bose, Chaudhuri and Hocquenghem (BCH) codes. Although conceived early in the history of coding theory, RS codes have only come into practical prominence in the last several years, due largely to the developments in VLSI processing technology that make the decoding computations feasible. The best evidence of the penetration of RS codes into modern practice is their use in compact disc players. RS codes have also recently become prominent in recording on magnetic and optical media, and high-speed single-chip decoders have been produced for certain standards.

4.5.1. Basic properties of RS codes

Reed Solomon (RS) codes have been selected for the following reasons. They achieve the largest possible code minimum distance for any linear code with the same encoder input and output block lengths. RS codes are particularly useful for burst-error correction and they are effective for channels that have memory. Moreover, they enable erasure-filling which is suitable for fading channels. For RS codes, the decoding error probability is an exponentially decreasing function of block length \( n \), and decoding complexity is proportional to a small power of the block length [Wicker]. RS codecs are available commercially. In the literature, there is widespread use of RS codes in hybrid-ARQ schemes [Shiozaki2,Deng93,Wicker9].

A Reed Solomon code is a \( q \)-ary BCH code of length \( q^n-1 \). It is defined over GF\( (q^n) \). Reed Solomon codes have a number of interesting properties that are not shared by other BCH codes. An \((n,k)\) RS code always has minimum distance of exactly equal to \((n-k+1)\). Thus, the code is able to correct \( t = (n-k)/2 \) symbols. The RS code is a member of the Maximum Distance Separable (MDS) family and therefore has the special property in satisfying the Singleton Bound.

The Singleton Bound states that, given a linear code with length \( n \) and dimension \( k \), the upper bound of the minimum distance \( d_{\text{min}} \) must satisfy the equality \( d_{\text{min}} \leq (n - k +1) \). An \((n,k)\) code that satisfies the
Singleton bound with equality is called MDS. This means that MDS codes provide "maximum distance" between code words.

4.5.2. Punctured RS codes

An \((n, k)\) RS code with rate less than one half is selected to represent the mother code. This code should provide sufficient error correction capability for the reliable transmission of information under the worst channel conditions expected.

The RS mother code is punctured to form code words in \(C_1\) and \(C_2\). The first \(n/2\) co-ordinates in the given \(C_3\) code word \(c_{i3}\) form the code word \(c_{i1}\) in \(C_1\), while the remaining \(n/2\) co-ordinates form the code word \(c_{i2}\) in \(C_2\). As these codes have the property of being invertible, the corrected versions of code words from any of the three codes can be used to recover the information symbols. One theorem concerning MDS codes states that any combination of \(k\) code-word coordinates in an MDS code may be used as message coordinates in a systematic representation. This automatically implies that any combination of \(k\) coordinates in an \((n,k)\) RS code can be treated as message positions.

The puncturing operation through the deletion of parity co-ordinates from each code word in the code affects the minimum distance of the resulting code. For this case, it is a function of the number of co-ordinates punctured. Through \(j\) puncturing operations, an \((n, k, n-k+1)\) MDS code becomes an \((n-j, k, n-k-j+1)\) code. The puncturing process is depicted in Figure 4-7. The code word \(c_{i3}\) is in the \((n,k,n-k+1)\) \(C_3\), code word \(c_{i1}\) is in the punctured \((n/2, k, n/2-k+1)\) \(C_1\), and code word \(c_{i2}\) is in the punctured \((n/2, k, n/2-k+1)\) \(C_2\).

The operation of the type-II hybrid with punctured RS codes is indicated in the flow diagram of Figure 4-7. A code word is encoded using two codes, \(C_1\) and \(C_2\), to create a pair of code word \(c_1\) and \(c_2\). For the initial transmission, \(c_1\) is sent while \(c_2\) is kept aside.
Chapter 4: The Data Link layer - protocol design issues and error control techniques

Upon receiving $c_1$, the receiver attempts decoding operation $D_1$ to recover the transmitted data. If the decoding operation is successful, an acknowledgement is sent. Otherwise, a retransmission is requested. The response of the transmitter is to send $c_2$. The receiver then attempts to decode $c_2$ by itself using decoding operations $D_2$. If successful, the receiver inverts the corrected version of $c_2$ to recover the desired information and sends an ACK to the receiver. If the operation is not successful, the receiver then combines $c_1$ and $c_2$ to create $c_3$, a code word in the lower rate code $C_3$. If the third decoding operation $D_3$ is successful, the data is recovered and an ACK is sent to the receiver. Else, a NAK is sent and the entire process is repeated.

Our hybrid strategy will incorporate punctured RS codes. Puncturing is a means of avoiding the complexity of decoders while having simple implementation. Given a fixed encoder structure, high-rate codes are achieved by periodically deleting bits from one or more of the encoder output streams. The puncturing technique has also been demonstrated in a number of hybrid-ARQ schemes [Hag1,2].

RS codes allow for very efficient means of erasure decoding. Given $e$ erased positions, the code still has a minimum distance of $d_{\min}-e$ between codewords, over all the unerased positions. We are therefore
able to correct \( t = (d_{\text{min}} - e - 1)/2 \) errors in these unerased places. As long as \( (2t + e) < d_{\text{min}} \), we can correct \( t \) errors and \( e \) erased positions. When an erasure occurs, the maximum likelihood decoding compares the received sequence with all codewords, but ignores the symbols valued in the erased positions. The erasures are filled using the values from the selected codeword.

4.6. **Interleaving**

In the LEO satellite communication channel, the fading process causes bursts of errors to appear with varying frequency and duration in the received data stream. The selection of very long codewords could function as an averaging process in spreading out the effects of the deep fades over the rest of the signal. On the other hand, decoder complexity is a function of code length and of the number of errors to be corrected. Both should be minimised if the resulting decoder structure is to be easily and inexpensively implemented.

Both criteria can be fulfilled using interleaving, which allows for the use of shorter codes and achieves the desired averaging effect. The interleaving technique allows for the effective use of random error correcting codes over bursty channels. It basically spreads out the effects of deep fades upon the code symbols. If the interleaver has sufficient depth, the noise and fading processes affecting adjacent codeword symbols will be uncorrelated. Then a memoryless channel model can be adopted to describe the error processes acting on the symbols within a given codeword.

Interleaving essentially makes the burst error patterns that predominate on the channel look like the purely random error patterns that typify the AWGN channel. Figure 4-8 depicts the operation of a block interleaver. \( \lambda \) codewords are read into an array, which each row consisting of one \( n \)-bit codeword. The array is read out column by column for transmission.

![Figure 4-8: Block Interleaving process](image-url)
4.7. The Feedback Channel

In almost all of the existing studies on ARQ protocols, the effects of channel errors are assumed to be independent from packet to packet. In practice, it is likely that channel errors in different slots are correlated. Research by Lu and Chang had considered the effect of non-independent channel errors, by examining $k$th-order Markovian errors and gap errors [Lu93]. Their key discovery is that when channel errors are dependent, selective-repeat ARQ achieves the same throughput efficiency as that with independent channel errors.

Morgera and Odoul investigated the effect of feedback channel errors on Markov channels for a more realistic evaluation [Oduol93]. The outcome of the investigation was that the feedback channel noise can result in the loss of packets, an increase in the number of undetected errors, and the occurrence of unnecessary transmission. The results presented in the paper are felt to be important for system design employing ARQ error control methods.

From the literature survey, it was discovered that most research has been performed assuming the feedback channel is noiseless. However, this assumption does not hold because in practical cases, the feedback channel in the LEO environment is subject to the effects of multipath fading and interference. The effects of the feedback channel are critical because an acknowledgement might be misinterpreted as a non-acknowledgement and this significantly affects the decision of the system. Lu and Chang have performed an analysis of return channel errors on the performance of ARQ protocols via signal flow graphs. The signal flow graph method can be used to analyse the effects of return channel error on the LEO satellite communications channel.
4.8. **OPNET Simulation tool**

OPNET is a comprehensive engineering system capable of simulating large communications networks with detailed protocol modelling and performance analysis [MIL88]. OPNET features include graphical specification of models, a dynamic event-scheduled Simulation Kernel, integrated data analysis toll and hierarchical object-based modelling.

![OPNET tools and modeling structure](image)

OPNET models are hierarchical. At the lowest level, the behaviour of an algorithm or protocol is encoded by a state/transition diagram with embedded code based on C language constructs. At the middle level, discrete functions such as buffering, processing, transmitting, and receiving data packets are performed by separate objects, some of which rely on an underlying process model. These objects, called modules, are created or modified using the Node Editor, and connected to form a higher level node model. At the highest level, node objects are connected by links to form a network model.

The SR sliding window protocol in the Broadcast Protocol has been implemented in the OPNET simulation tool. It is reviewed as follows.
4.8.1. The Network

In OPNET, Network Domain defines the topology of a communication network in terms of sub-networks, nodes, links and geographical content. In this thesis, the network model consists of a satellite node, a groundstation node and a LEO communications link.

4.8.2. The Nodes

In the Node domain, modules are classified into information sources, sinks, processors and queues. Processors and queues are highly user-programmable and its behaviour is described by an assigned process model. In the Node domain, a device that relies on a particular stack of protocols can be modeled by creating a 'processor' object for each layer of that stack.

![Layered protocol architecture](image)

As in Figure 4-10, a packet generator and sink functions at the Network layer. The data-link layer is represented by a 'processor' which does the necessary error detection, discard of packets, sending the packets to the Network layer, generating ACKs, requests for repeats, etc. The physical layer is represented by a transmitter and receiver.

4.8.3. The LEO communications link

The most prevalent form of communications in OPNET models is based on the general notion of messages that can carry information and be sent between subsystems. In OPNET, packets are data structures defined in order to support message-oriented communications. Packets can be created, modified, copied, sent, received and destroyed. The implementation of the communications link is a sequentially executed set of stages. Once a packet is sent to the transmitter, the each stage sequence is executed once for each packet.

![Stages in the communications link](image)
Chapter 4: The Data Link layer - protocol design issues and error control techniques

The first stage in the link is the computation of the time it takes for transmission delay and propagation delay through the channel. The next error allocation stage will allocate the errors to the packets, based on the raw data measured from the channel as in Chapter 3 or the newly developed Fritchman or 4-state probabilistic channel. Each packet that arrives at the receiver will initially be detected for errors.

4.8.4. The Process Domain

Processes respond to interrupts which indicate that events of interest have occurred, such as the arrival of a message. When a process is interrupted, it takes the necessary actions in response, and then block and waits for a new interrupt. It may also invoke another process.

![Figure 4-12: Example of an FSM in OPNET](image)

The components of a process model include a finite state machine (FSM) diagram with embedded C statements, and various blocks containing code for variable declarations, macros, constants, and function definitions. These components are collectively termed Proto-C, since they define a variant of the C language specialized for protocols and distributed algorithms. The FSM diagram represents the functional flow of the process with an easily interpreted diagram of states and transitions. States typically, contain C-syntax statements, called state executives, which perform a specific task. Events and conditions determine the migration from state to state through transitions. The following diagram shows a generic representation of a simple FSM. Each circle represents a state; the arrow between states represent transitions. The implementation of the protocol is described.
4.9. **The Selective Repeat Protocol Design Issues**

In this section, we examine the underlying mechanism of sliding window protocols, namely the selective repeat (SR) protocol. The network layer builds a *packet* by taking a message from the transport layer and adding the network layer header to it. A *packet* is the unit of information exchanged between the network layer and the data link layer on the same machine, or between network layer peers. This packet is passed to the data link layer.

At the data link layer, the packet is encapsulated into a frame which consists of four fields: *kind*, *seq*, *ack*, and *info*. The *kind* field differentiates between data or acknowledgement content in the frame. The *seq* and *ack* fields are used for sequence numbers and acknowledgement respectively, and the *info* field contains a single *packet*.

Sequence numbers enable the receiver to check each arriving frame to determine whether it is a new frame, a duplicate to be discarded, or a retransmission. It also fulfils the requirements of delivering packets to the destination network layer in the same order that they were passed to the data link layer on the sending machine. Duplicate or damaged frames are not sent to the network layer. The acknowledgement field contains the number of the last frame received without error. If this number agrees with the sequence number of the frame the sender is trying to send, the sender knows it is done with the frame stored in buffer and can fetch the next packet from its network layer.

The essence of all sliding window protocols is that at any instant of time, the sender maintains a list of consecutive sequence numbers corresponding to frames it is permitted to send. These frames are said to fall within the *sending window*. Similarly, the receiver also maintains a *receiving window* corresponding to frames it may accept. The sequence numbers within the sender's window represent frames sent but not yet acknowledged. Whenever a new packet arrives from the network layer, it is given the next highest sequence number and the upper edge of the window is advanced by one. When an ACK comes in, the lower edge of the sending window is advanced by one. Through this procedure, the window continuously maintains a list of unacknowledged frames. All these frames are kept in memory for possible retransmission. Thus, if the maximum window size is \( n \), the sender requires \( n \) buffers to hold the unacknowledged frames. If the window ever grows to its maximum size, the sending data link layer must forcibly shut off the network layer until another buffer becomes free. Effectively, there is a timer associated with each buffer. When the timer runs out, the contents of the buffer are retransmitted.

The receiving data link layer's window corresponds to the frames it may accept. Any frame falling outside this window is discarded. When a frame whose sequence number is equal to the lower edge of the window is received, it is passed to the network layer, an ACK is generated and the window is rotated by one. Unlike the sender's window, the receiver's window always remains at its initial size.
The operation of the sliding window protocol is best illustrated in the FSM of Figure 4-13. The process begins with a short initialisation phase and automatically enters the idle state. Here, the data link layer waits for an interrupt associated with an event. These events can be categorised into NetworkLayerReady, FrameArrival, CksumError, Timeout and NL-Idle and are detailed as follows.

4.9.1. Event NetworkLayerReady

Event NetworkLayerReady occurs when the network layer is permitted to transmit a packet to the data link layer. Through the process of enabling and disabling the network layer, the data link layer can prevent the network layer from swamping it with packets for which it has not enough buffer space. The sender begins by fetching a packet from the network layer, constructs the necessary outbound frame and sends the frame to the physical layer where it is transmitted. At the receiver, it waits for the packet to arrive (represented by event FrameArrival). Finally, the data portion is passed on to the network layer and the data link layer settles back to wait for the next frame.

After transmitting a frame, the sender starts the timer running. If it was already running, it will be reset to allow another full timer interval. The time interval of the timer must be selected to allow sufficient time for the frame to arrive at the receiver, for the receiver to process it in the worst case, and for the corresponding ACK frame to propagate back to the sender. Only when that time interval has elapsed is it safe to assume that either the transmitted frame or its ACK has been lost, and to send a duplicate.

Because the SR protocol has multiple outstanding frames, it logically needs multiple timers, one per outstanding frame. Each frame times out independently of all the other ones.
Since a sender may have to retransmit all the unacknowledged frames at a future time, it must hang on to them until it knows for sure that they have been accepted by the receiver. Whenever any ACK comes in, the data link layer checks to see if any buffers can now be released. If buffers can be released, a previously blocked network layer can now be allowed to cause more NetworkLayerReady events.

4.9.2. Event FrameArrival

When a frame arrives either at the transmitter or receiver, this is denoted by event FrameArrival. At the transmitting end, FrameArrival may indicate three possibilities: an ACK frame which arrives undamaged, a damaged ACK frame that staggers in, or the timer going off. If a valid ACK arrives, the sender fetches the next packet from its network layer and puts it in the buffer, overwriting the previous packet. It also advances the sequence number. Under no conditions will the receiver ever accept frames whose sequence numbers are below the lower edge of the window or frames whose sequence number are above the upper edge of the window. When a valid frame arrives at the receiver, its sequence number is checked if it is a duplicate. If that is not the case, the frame is accepted, passed to the network layer, and an ACK generated. The receiver will wait until the network layer passes it the next packet and piggybacks the ACK onto the next outgoing data frame.

4.9.3. Event CksumError

Event CksumError occurs when the receiver detects an erroneous frame. During such occurences, the receiver automatically discards the frame. Whenever the receiver has reason to suspect that an error has occurred, it sends a negative acknowledgement (NAK) frame to the sender. Such a frame is a request for retransmission of the frame specified in the NAK. To avoid making multiple requests for retransmission of the same lost frame, the receiver should keep track of whether a NAK has already been sent for a given frame. If the NAK gets mangled or lost, no real harm is done, since the sender will eventually time out and retransmit the missing frame anyway.

Closely related to the matter of timeouts and NAKs is the question of determining which frame caused a timeout. In SR, there is no trivial way of determining which frame timed out. We assume that the variable OldestFrame is set upon timeout to indicate which frame had timed out.

4.9.4. Event NetworkIdle

If a new packet arrives quickly, the acknowledgement is piggybacked onto it; otherwise, if no new packet has arrived by the end of this time period, the data link layer just sends a separate acknowledgement frame. This is indicated by event NetworkIdle.
4.9.5. Event Timeout

In most of the protocols, we assume an unreliable channel that loses entire frames upon occasion. To be able to recover from such calamities, the sending data link layer must start an internal timer or clock whenever it sends a frame. If no reply has been received within a certain predetermined time interval, the clock times out and the data link layer receives an interrupt signal.

4.10. Summary

This chapter has discussed the PBP protocol currently used by the fleet of microsatellites in LEO. It has recommended the introduction of FEC for such a system, and proposed a hybrid-ARQ scheme. The literature on hybrid-ARQ schemes has been extensive. A literature survey on existing hybrid-ARQ schemes has been performed in order to enable the selection of hybrid schemes based on the requirements of the SSTL LEO satellite link. The selection process has tended to favour Reed-Solomon codes. Several coding techniques like interleaving, puncturing and erasures seem promising as they possess the properties of noise averaging and provide extra levels of adaptivity through different code rates, according to the varying channel conditions. For the final sections of this chapter, the OPNET simulation tool is introduced. The setup of the simulation environment in OPNET from the Network, Data link to Physical layer is described. A detailed implementation of the SR protocol is reviewed.
4.11. References


Chapter 4: The Data Link layer - protocol design issues and error control techniques


Chapter 5

The Performance Of Error Control Strategies

5.1. Introduction

This chapter presents all investigations, results and discussions on the selection of the optimal code rate, hybrid scheme and coding technique for a range of LEO satellite elevation angles. These discussions are essentially grouped into three categories, covering simulations performed on the type-II hybrid, the type-II + delay hybrid and block interleaving. In the first section of this chapter, the tradeoffs that need to be considered in the selection of a code, based on the requirements and applications of the current system, are analysed in depth.

It has been essential to evaluate how closely the Fritchman and 4-state models predict the measured sequences through simulations with the type-II RS hybrid. Therefore, in the next section, comparisons are made between the corresponding Fritchman and 4-state models with the in-orbit data (as detailed in Chapter 3) in terms of type-II performance. A decision is subsequently made to select the generative model that more accurately matches the observed statistics so that longer simulations can be performed.

It is necessary to examine the effects of the channel for longer periods of time to obtain more reliable statistics, hence further 'real' case simulations have been carried out in OPNET. In the process of conducting these simulations, the impact of propagation delays through the channel and processing delays on the type-II hybrid are investigated. The optimal codes to be employed for each elevation angle are suggested and protocol issues such as buffering considerations and timeouts of packets presented in Chapter 4 are examined.

A novel type-II + delay hybrid has been introduced in this chapter and the effectiveness of this protocol is investigated especially during periods of interference. In contrast to the aforementioned error control techniques, the performance of block interleaving techniques on the channel are also evaluated.
Chapter 5: The Performance of Error Control Strategies

Similar to the type-II hybrid, comparisons are again made between the measured data and the generated data from the corresponding Fritchman and four-state models based on byte interleaving. A survey is conducted to select the optimal byte interleaved code for different elevation angles. Finally, the amount of improvement the type-II, type-II + delay and byte interleaving schemes can provide for the existing PB protocol is listed. This chapter concludes by listing the type of codes and hybrid scheme worth considering for the existing protocol.

5.2. General Considerations in Trade-off

Before proceeding to the performance evaluations, it is crucial to examine the various tradeoffs that need to be taken into consideration when selecting an error control code. This selection is dependent upon the nature of the propagation channel, the structure of the data and any requirements of users. The principal design criteria that must be satisfied, based on the existing and operating PB platform, are that the code should result in a lower overall system cost and must be able to substantially improve the data throughput of the system. In terms of constraints in bandwidth, the code rate should be maximised, which implies that the amount of redundancy required should be minimised. However, care must be taken in not over designing the code for the best conditions, providing lower error rates than are necessary in coping with the worst-case conditions. More importantly, this coding scheme should ideally show the flexibility in coping with a wide range of possible conditions, hence showing adaptivity to different error rates of the channel.

To fulfill the requirements of types of applications, the coding technique should demonstrably be suitable for packet communications. In terms of implementation issues, the hardware of the code should be simple so as to minimise cost. Furthermore, consideration is required if the codec is available commercially or needs to be developed specifically. In general, the code has to provide a cost-effective solution, to reduce the power requirement for a given error rate as there is limited power available on the microsatellite.

The performance of the type-II RS hybrid has been analysed for multiple satellite passes at maximum elevation angles ranging from $15^\circ$ to $74^\circ$. Plots of the percentage of packets that pass the decoding process versus various code rates for a range of elevation angles are depicted in Graphs 5-1 to 5-8. It is observed that as the rate of the code increases, the number of packets that are decodable gradually decreases. This can be attributed to the fact that less redundancy provided by the code will result in fewer parity bits for error correction and a lower error-correction capability, therefore fewer packets will be successfully decoded.

A good choice of codes will involve the best trade-off between the coding rate and the number of packets that are decodable. In addition, the efficiency of the protocol, which is given by the product of the code rate and the percentage of packets that pass needs to be taken into account. As reviewed in the previous chapter, the throughput performance of a SR protocol is a function of the code rate employed and its efficiency. Another trade-off to be considered is the amount of error detection provided by each
(n,k) code. The Hamming bound states that the number of syndromes is at least equal to the number of correctable error patterns. For an (n,k) code based q-ary symbol, any error can take q-1 possible values, and the expression for any q-ary code that can detect and correct t errors is described by:

\[ q^{n-k} \geq \sum_{i=0}^{t} \binom{n}{i} (q-1)^i \]  

(5-1)

The expression on the right of the equation, S is the number of syndromes for which the decoder has an output. The term on the left, T is the total number of syndromes for an (n,k) code defined over GF(q).

Let us denote that the channel produces non-correctable errors with a probability of \((1 - P_{corr})\), where \(P_{corr}\) is the probability of a correctable error. If this happens, the probability of an incorrect output is equal to the probability that the syndrome will be one of \(S\) (rather than of the larger set \(T\)) which implies that

\[
\frac{\text{Probability of incorrect decoding}}{(1 - \text{Probability of correctable error})} \leq \frac{\sum_{i=0}^{t} \frac{n!}{i!(n-i)!} (q-1)^i}{q^{n-k}}
\]

(5-2)

For example, it is calculated that the probability of a (128,120) Reed-Solomon code providing incorrect decoding is 1 in 400, whereas for a (128,112) code is around \(10^{-7}\). As the amount of error detection needs to be reliable, one would select a baseline of around \(10^{-6}\) of decoding reliability as a reasonable value of error detection.

### 5.3. Evaluating the accuracy of models against coding performance

In Section 3, the cumulative burst lengths and burst gaps for the measured data and data generated from the Fritchman and 4-state models have been evaluated, compared and presented. The general conclusion was that the one-error and two- or three-good state Fritchman model is able to closely fit the observed sequences - more accurately than the 4-state model for all the elevation angles considered when there are no effects of unpredictable interference and burst clustering at high elevation angles.

To verify this statement, the error sequences of these two sets of data (the Fritchman and 4-state models) are again evaluated against different coding rates of the type-II RS hybrid scheme. The closer fit of the two models to the measured data will be chosen and simulated for its longer term effects in OPNET. The throughput performance versus coding rate for the type-II scheme is illustrated in Graphs 5-1 to 5-8 on the next page. Each graph compares the percentage of decodable packets for the measured data and generated data from the Fritchman and 4-state models.
Chapter 5: Performance of Error Control Schemes

Graph 5-1: Experimental data vs. Generated data from 4-state and Fritchman model for a 15° satellite pass

Graph 5-2: Experimental data vs. Generated data from 4-state and Fritchman model for a 23° satellite pass

Graph 5-3: Experimental data vs. Generated data from 4-state and Fritchman model for a 30° satellite pass

Graph 5-4: Experimental data vs. Generated data from 4-state and Fritchman model for a 40° satellite pass

Graph 5-5: Experimental data vs. Generated data from 4-state and Fritchman model for a 52° satellite pass

Graph 5-6: Experimental data vs. Generated data from 4-state and Fritchman model for a 63° satellite pass
5.3.1. Model comparisons at 15°

For a 15° satellite pass, the results exhibited from the three-good state one-error state Fritchman model are within 4% to the experimental data for the worst case. This holds for (128,114) coding rates and all cases of lower coding rates. The exception is the (128,120) code in which the result deviation is 10% from the experimental data in terms of error performance.

For the four-state model, the (128,120) performance is accurate to within 0.3% of the real results. However, at slightly lower code rates, the results display a larger deviation (7%) from the measured data compared to the Fritchman model although both models are good at the lower rates. In terms of mothercode decoding operations, both Fritchman and 4-state models are able to recover the repeats 100%. There is no obvious indication which model is the better in predicting the observed error sequences. In the previous Chapter 3, comparisons were made between the cumulative burst lengths and gaps amongst the two models. The conclusion was that the Fritchman model provided a closer fit to the experimental data for both plots, therefore it is selected to model the channel at this elevation angle.

5.3.2. Model comparisons at 23°

At 23°, both the Fritchman and 4-state models predict the observed protocol performance closely. The Fritchman model predicts to within 0.2% for the worst case while the 4-state model predicts all results to within 0.3%. From observing the plots, the Fritchman model gives a 100% success in decoding for the (128,116) code and all lower code rates. This result is also demonstrated in the experimental in-orbit data. In terms of mothercode decoding, there is no need for such an operation for both the Fritchman and experimental data.

For the 4-state model, the decoding success is not 100% for the (128,116) code, but with further increases in redundancy, the decoding process eventually reaches 100%. It was simulated for the 4-state model that 3 packets were employed in the mothercode decoding operation out of a total of 48828
Chapter 5: Throughput performance of Coding Techniques

packets. The 4-state model seems to generate a fraction of more errors than the observed error statistics of the channel. Nevertheless, the results are very near to what is anticipated. It is decided that the Fritchman model can more accurately predict the statistics of the measured data for the various code rates and will therefore be utilised for further longer term simulations.

5.3.3. Model comparisons at 30°

At a 30° satellite pass, both the Fritchman and 4-state models provide an accuracy which is within 0.5% to the experimental data in the worst case. It is observed that the Fritchman model is slightly pessimistic in the results while the 4-state model is slightly more optimistic than the actual data. It can be deduced from the performance tables in Section 5.3.4 that 43 packets out of nearly 50,000 packets are utilised in the operation of the mothercode for the 4-state model. On the other hand, there is no requirement for mothercode decoding for both the experimental data and that generated from the Fritchman model. For this elevation angle, both Fritchman and 4-state models are accurate in predicting the error sequences. However, the preference is the 3-good state 1-error state Fritchman model as it is more precise.

5.3.4. Model comparisons at 40°

For a satellite pass at 40°, both models are very close to the original results and are within 0.3% in the worst case. In terms of mothercode decoding, there is no need in this operation as exhibited in the experimental, Fritchman and 4-state models. Again, the Fritchman model is preferable to the 4-state model as it is obvious from the plots that the Fritchman model is the better choice.

5.3.5. Model comparisons at 52°

The discussion thus far has covered the cases in which both Fritchman and 4-state model represent the observed error statistics of the channel well. However, for the following two elevation angles, the results are quite unexpected as displayed in the cumulative plots and discussions in Chapter 3.

At the elevation angle of 52°, further analysis of the percentage of packets that have passed the decoding process versus various coding rate reveals that the 4-state model is able to closely predict the error statistics of the measured data to within 4% of the results in the worst case. As for the Fritchman model, the exhibited results show a deviation of 23%. From the cumulative plots of burst lengths and burst gaps in Chapter 3, the Fritchman model closely fits the measured data. However, the results exhibited from the Fritchman model based on type-II performance significantly differs from the original experimental data. Therefore, it is decided that the Fritchman model cannot represent the observed error statistics and that the error processes cannot be described by one error state. For this elevation angle, the 4-state model is selected to represent the error conditions.
5.3.6. Model comparisons at 63°

At a satellite pass at 63°, the Fritchman model predicts the performance to within 0.2% of the original results while the 4-state model is within 0.3% in the worst case. The mothercode decoding operation is not utilised as demonstrated in results from the 4-state and Fritchman models and experimental data. It seems that the Fritchman model is again closer to the experimental data and therefore is selected.

5.3.7. Model comparisons at 68°

At the higher elevation angles of 68°, there is no clear indication which is the better model to represent the measured statistics. Simulations with the (128,120) code indicate a 10% deviation in results from the Fritchman and a 6% deviation from the 4-state model. However, at the lower code rates, the Fritchman model gives a closer fit to the measured data than the 4-state model. From (128,112) and at the lower coding rates, the worst case deviation from the Fritchman model is 4% whilst the 4-state model provides a 11% discrepancy in the result. As explained in Section 3, the results displayed by the Fritchman model in terms of its cumulative burst lengths and gaps is closer to the experimental data than the 4-state model. Therefore, the Fritchman model is again selected.

5.3.8. Model comparisons at 74°

For the last range of elevation angle at 74°, it is obvious from the plots that a Fritchman model can not represent the observed error statistics. Instead, a reasonable approximation can be supplied by the 4-state model. Therefore, the 4-state model is selected for longer term simulations.
5.4. **Type-II hybrid performance**

In this section, the various tradeoffs are discussed and the optimal code RS code for each elevation angle is suggested.

5.4.1. **Type-II Performance at 15°**

In this section, the optimal code for each elevation angle considered is discussed in detail. Each of the graphs in Section 5.3 are reproduced in all sub-sections for clarity and comparison purposes. The results of the type-II hybrid scheme performance of various codes for a satellite pass at 15° are depicted in table 5-1. A (128,k) punctured Reed Solomon code is employed for the encoding process. When both halves of the punctured (128,k) Reed-Solomon code have failed the decoding process, these two transmissions are combined and decoded with the (256,k) mothercode. This table lists the number of packets that have passed, failed and the percentage of passes for the first decoding process through a (128,k) punctured RS code. The number of subsequent repeats that required the mothercode decoding process are also listed. This is denoted as x/y, where x and y are the number of repeats that have passed or failed the mothercode decoding respectively.

![Graph 5-1: Experimental data vs. Generated data from 4-state and Fritchman model for a 15° satellite pass](image)

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,16)</td>
<td>1776</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(128,32)</td>
<td>1775</td>
<td>1</td>
<td>99.94</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(128,64)</td>
<td>1765</td>
<td>11</td>
<td>99.38</td>
<td>3/0</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(128,96)</td>
<td>1727</td>
<td>49</td>
<td>97.24</td>
<td>16/0</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(128,104)</td>
<td>1694</td>
<td>82</td>
<td>95.38</td>
<td>24/1</td>
<td>4876</td>
<td>6</td>
<td>99.88</td>
<td>-</td>
<td>4838</td>
<td>44</td>
<td>99.10</td>
<td>2/0</td>
</tr>
<tr>
<td>(128,112)</td>
<td>1614</td>
<td>162</td>
<td>90.88</td>
<td>53/3</td>
<td>4783</td>
<td>99</td>
<td>97.97</td>
<td>3/0</td>
<td>4473</td>
<td>409</td>
<td>91.62</td>
<td>37/0</td>
</tr>
<tr>
<td>(128,116)</td>
<td>1524</td>
<td>252</td>
<td>85.81</td>
<td>90/2</td>
<td>4518</td>
<td>364</td>
<td>92.54</td>
<td>36/0</td>
<td>4035</td>
<td>847</td>
<td>82.65</td>
<td>161/0</td>
</tr>
<tr>
<td>(128,120)</td>
<td>1392</td>
<td>384</td>
<td>78.38</td>
<td>141/5</td>
<td>3812</td>
<td>1070</td>
<td>78.08</td>
<td>274/0</td>
<td>4882</td>
<td>1572</td>
<td>67.80</td>
<td>417/0</td>
</tr>
</tbody>
</table>

For a 15° satellite pass, from simulations with the experimental data, the number of packets with correctable errors is 78.38% for a (128,120) RS code. However, not all the packets are successfully
decoded with the mothercode operation. As observed from Table 5-1, 141 out of 146 repeats are recovered. The optimal code is a (128,112) code which recovers 90.88% of the packets with an efficiency of 79.52%, for the first decoding attempts at the receiver. For the rest of the packets that have failed to be decoded, these are retransmitted and it is estimated that 96% of the repeats are recovered with the mothercode. Altogether, 99.64% of all packets can be recovered. Comparisons with the four-state model for a (128,112) code provide a 97.97% estimate of the packets being successfully decoded with an efficiency of 85.73% which is more optimistic than the measured data. The 3-good state 1-error state Fritchman model precisely predicts the performance of the (128,112) code with a 91.62% packet recovery and efficiency of 80.17% while all repeats are successfully recovered with the mothercode.

5.4.2. Type-II performance at 23°

For satellite passes at 23°, 30° and 40°, the number of packets recovered is at least 98.41% for a (128,120) RS code at the first decoding attempts for the experimental data and sequences generated from the corresponding 4-state and Fritchman models. It has been demonstrated from simulations on the experimental data and Fritchman models that there is no requirement for the type-II hybrid mothercode operation. A simple (128,k) FEC code employed with the current SR-ARQ protocol is sufficient to overcome the errors in the channel for these elevation angles. These claims are further discussed as follows.

<table>
<thead>
<tr>
<th>EXPERIMENTAL DATA</th>
<th>GENERATED DATA FROM 4-STATE</th>
<th>GENERATED FROM FRITCHMAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODE</td>
<td>PASS</td>
<td>FAIL</td>
</tr>
<tr>
<td>(128,64)</td>
<td>2022</td>
<td>0</td>
</tr>
<tr>
<td>(128,96)</td>
<td>2022</td>
<td>0</td>
</tr>
<tr>
<td>(128,104)</td>
<td>2022</td>
<td>0</td>
</tr>
<tr>
<td>(128,112)</td>
<td>2022</td>
<td>0</td>
</tr>
<tr>
<td>(128,116)</td>
<td>2022</td>
<td>0</td>
</tr>
<tr>
<td>(128,120)</td>
<td>2013</td>
<td>9</td>
</tr>
</tbody>
</table>

Graph 5-2: Experimental data vs. Generated data from 4-state and Fritchman model for a 23° satellite pass

Table 5-2: Results of (128,k) punctured code for a 23° satellite pass
At 23°, the optimal code is a (128,120) code that decodes 99.55% of the packets at an efficiency of 93.33%. With a slight increase in redundancy, 100% of the packets are correctable through utilising a (128,116) RS code. Taking into account the efficiency of the protocol, the optimal code from the generated 4-state model is also a (128,120) which can correct 99.27% of the packets at an efficiency of 93.06%. On the other hand, for the 2-good state and 1-error state Fritchman model, the optimal code is also (128,120) that corrects 99.73% of the packets at an efficiency of 93.5%. Ideally one would like to select the (128,120) RS code based on its high success in number of decodable packets. However, it does not provide sufficient reliability in correct decoding of the packets. Therefore, the (121,112) code is chosen for this range of elevation angles.

5.4.3. Type-II performance at 30°

At 30°, for the experimental data, a (128,120) code provides 98.92% of the packets successfully decoded with a high efficiency of 92.74%. The results with further simulation is similar for the 4-state model with the same (128,120) code that gives 98.41% success in decoding at an efficiency of 92.26%. Finally, for the Fritchman model, the (128,120) code provides the highest throughput of packets that are recovered at 99.61% at an efficiency of 93.39%. It is observed from Table 5-3 that 43 packets out of nearly 50,000 packets are utilised in the operation of the mothercode for the 4-state model. On the other hand, there is no need for the mothercode combination for the experimental and 3-good state 1-error state Fritchman models. From the huge selection of coding rates, the best choice seems to be the

![Graph 5-3: Experimental data vs. Generated data from 4-state and Fritchman model for a 30° satellite pass](image)

Table 5-3: Results of (128,k) punctured code for 30° satellite pass

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,16)</td>
<td>1114</td>
<td>0</td>
<td>100.0</td>
<td>-</td>
<td>48828</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(128,32)</td>
<td>1114</td>
<td>0</td>
<td>100.0</td>
<td>-</td>
<td>48827</td>
<td>1</td>
<td>99.99</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(128,64)</td>
<td>1114</td>
<td>0</td>
<td>100.0</td>
<td>-</td>
<td>48826</td>
<td>2</td>
<td>99.99</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(128,96)</td>
<td>1113</td>
<td>1</td>
<td>99.91</td>
<td>-</td>
<td>48769</td>
<td>59</td>
<td>99.88</td>
<td>1/0</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(128,104)</td>
<td>1113</td>
<td>1</td>
<td>99.91</td>
<td>-</td>
<td>48685</td>
<td>143</td>
<td>99.71</td>
<td>1/0</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(128,112)</td>
<td>1110</td>
<td>4</td>
<td>99.64</td>
<td>-</td>
<td>48522</td>
<td>306</td>
<td>99.37</td>
<td>7/0</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(128,116)</td>
<td>1108</td>
<td>6</td>
<td>99.46</td>
<td>-</td>
<td>48343</td>
<td>485</td>
<td>99.01</td>
<td>20/0</td>
<td>4878</td>
<td>4</td>
<td>99.92</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(128,120)</td>
<td>1102</td>
<td>12</td>
<td>98.92</td>
<td>-</td>
<td>48054</td>
<td>774</td>
<td>98.41</td>
<td>43/0</td>
<td>4863</td>
<td>19</td>
<td>99.61</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

At 30°, for the experimental data, a (128,120) code provides 98.92% of the packets successfully decoded with a high efficiency of 92.74%. The results with further simulation is similar for the 4-state model with the same (128,120) code that gives 98.41% success in decoding at an efficiency of 92.26%. Finally, for the Fritchman model, the (128,120) code provides the highest throughput of packets that are recovered at 99.61% at an efficiency of 93.39%. It is observed from Table 5-3 that 43 packets out of nearly 50,000 packets are utilised in the operation of the mothercode for the 4-state model. On the other hand, there is no need for the mothercode combination for the experimental and 3-good state 1-error state Fritchman models. From the huge selection of coding rates, the best choice seems to be the
(128,112) code that gives a slightly lower percentage of successfully decoded packets at 99.64% (efficiency of 87.19%), 99.37% (efficiency of 86.95%) and 100% (efficiency of 87.5%) for the experimental data, 4-state and Fritchman models respectively.

5.4.4. Type-II performance estimates at 40°

For a satellite pass at 40°, weighing the tradeoffs between redundancy and throughput performance, the optimal code is a (128,112) code that decodes 99.93% of all packets at the first decoding attempt at an efficiency of 87.44% for the experimental data. The 4-state model also displays similar results with the optimal (128,112) code that decodes 100% of the packets at an efficiency of 87.5% while the same code gives 99.98% of success in decoding at an efficiency of 87.48% for simulations on the Fritchman model. For all three models, there is no need for the decoding operation of the mothercode.
5.4.5. Type-II performance at 52°

At the elevation angle of 52°, the scenario is different from the results previously encountered as we investigate the effects of unpredictable interference in the channel. From Section 5.3, through analysing the plots of the percentage of packets that passed versus the coding rate, it is deduced that the 4-state model is able to more accurately predict the error statistics of the measured data than the Fritchman model.

Based on simulations with the experimental data, the optimal code is the (128,96) that gives 79.46% of successfully decoded packets in the first decoding attempt at an efficiency of 59.60%. For the 4-state model, a (128,96) code gives 82.21% of success in the decoding of the packets at an efficiency of 55.15%.

For the experimental data, out of 79.46% of the packets that were successfully decoded, the number of repeats recovered is 90.32% with the mothercode, therefore amounting to a total sum of 98.01% of the packets recovered. On the other hand, for the 4-state model, 100% of the remaining retransmitted packets are totally decoded by the mothercode operation.

It can therefore be summarised that during the effects of unpredictable interference, the hybrid-type-II scheme is essential to recover the packets. However, this protocol is subject to multiple retransmissions. To ensure almost 100% recovery of packets, a (128,64) code is required based on simulations on the experimental data and data generated from the corresponding 4-state model.
5.4.6. Type-II performance at 63°

For a satellite pass at 63°, we find that at least 99.78% of the packets are successfully decoded from a (128,120) code at an efficiency of at least 93.75% for all the cases of simulations with the measured data, Fritchman and 4-state models. The mode code operation is again not required in all simulations. These results equally hold for the data generated from the 4-state and Fritchman models.

It can be deduced that the SR protocol with a high-rate FEC code can handle the burst errors for this elevation angle easily.
Chapter 5: Throughput performance of Coding Techniques

5.4.7. Type-II performance at 68°

Graph 5-7: Experimental data vs. Generated data from 4-state and Fritchman model for a 68° satellite pass

Table 5-7: Results of (128,k) punctured code for 68° elevation

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,16)</td>
<td>640</td>
<td>2</td>
<td>99.69</td>
<td>0</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(128,32)</td>
<td>640</td>
<td>2</td>
<td>99.69</td>
<td>0</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(128,64)</td>
<td>638</td>
<td>4</td>
<td>99.38</td>
<td>50</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4882</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(128,96)</td>
<td>607</td>
<td>35</td>
<td>94.55</td>
<td>83.33</td>
<td>4874</td>
<td>8</td>
<td>99.84</td>
<td>-</td>
<td>4836</td>
<td>46</td>
<td>99.06</td>
<td>-</td>
</tr>
<tr>
<td>(128,104)</td>
<td>577</td>
<td>65</td>
<td>89.88</td>
<td>90.00</td>
<td>4801</td>
<td>81</td>
<td>98.34</td>
<td>100</td>
<td>4575</td>
<td>307</td>
<td>93.71</td>
<td>100</td>
</tr>
<tr>
<td>(128,112)</td>
<td>503</td>
<td>139</td>
<td>78.35</td>
<td>94.12</td>
<td>4410</td>
<td>472</td>
<td>90.33</td>
<td>100</td>
<td>3768</td>
<td>1114</td>
<td>77.18</td>
<td>100</td>
</tr>
<tr>
<td>(128,116)</td>
<td>461</td>
<td>181</td>
<td>71.81</td>
<td>95.77</td>
<td>3896</td>
<td>986</td>
<td>79.80</td>
<td>100</td>
<td>3083</td>
<td>1799</td>
<td>63.15</td>
<td>100</td>
</tr>
<tr>
<td>(128,120)</td>
<td>375</td>
<td>267</td>
<td>58.41</td>
<td>98.17</td>
<td>3157</td>
<td>1723</td>
<td>64.67</td>
<td>100</td>
<td>2303</td>
<td>2579</td>
<td>47.17</td>
<td>100</td>
</tr>
</tbody>
</table>

At the higher elevation angle of 68°, the channel displays a more bursty error condition as previously discussed in Chapter 3. We therefore can anticipate a lower performance in the throughput for the same coding rates at this elevation angle compared to the results obtained for the lower elevation angles of 20° to 40° and 63°. For the experimental data, the optimal code is (128,104) for 89.88% of the packets decoded at an efficiency of 73.02% while 90% of the repeats are recovered with the mothercode.

As for the 4-state model, the optimal (128,104) code gives 98.34% of success in decoding at an efficiency of 79.9% while all packets are recovered using the mothercode operation. Finally, compared with the Fritchman model, the optimal code is also a (128,104) which decodes 93.71% packets at an efficiency of 76.14%. 

5-14
5.4.8. Type-II performance at 74°

For the last elevation angle at 74°, the throughput of the type-II protocol is extremely low. From simulations with the measured data, the optimal code is a (128,64) which successfully decodes only 44.27% of the packets at a very low efficiency of 22.14%. Only a third of the packets (34.04%) are recovered with the mothercode decoding operation. It is obvious from the plots that a Fritchman model cannot represent the observed error statistics. Instead, a reasonable approximation can be supplied by the 4-state model. For this model, simulations show that the optimal code is also a (128,64) code that guarantees 45.54% packets recovered at an efficiency of 22.77% while the mothercode operation can recover 24.21% of the retransmitted repeats.
5.4.9. Improvement compared to ARQ-only system

Table 5-9 below illustrates and compares the total throughput performance of the current operating SR-ARQ PB protocol based upon a range of elevation angles. As previously mentioned, the presence of any errors in a packet results in a decision taken to reject such a packet in the PB protocol. A simple calculation is therefore performed to examine each packet if it contains any errors and to keep count of the packets that are error-free and erroneous and the throughput performance is computed.

<table>
<thead>
<tr>
<th>RANGE OF ELEVATION ANGLES</th>
<th>THROUGHPUT PERFORMANCE OF PB</th>
<th>THROUGHPUT ACHIEVED FROM THE TYPE-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>12° - 15°</td>
<td>16.10 %</td>
<td>90.88 %</td>
</tr>
<tr>
<td>17° - 23°</td>
<td>76.95 %</td>
<td>100 %</td>
</tr>
<tr>
<td>25° - 30°</td>
<td>57.45 %</td>
<td>99.64 %</td>
</tr>
<tr>
<td>34° - 40°</td>
<td>90.22 %</td>
<td>99.93 %</td>
</tr>
<tr>
<td>48° - 52°</td>
<td>1.08 %</td>
<td>79.46 %</td>
</tr>
<tr>
<td>58° - 63°</td>
<td>90.31 %</td>
<td>100 %</td>
</tr>
<tr>
<td>64° - 68°</td>
<td>4.67 %</td>
<td>89.88 %</td>
</tr>
<tr>
<td>70° - 74°</td>
<td>9.04 %</td>
<td>44.27 %</td>
</tr>
</tbody>
</table>

The throughput performance achieved based on the optimal code which was suggested in the previous sections for each elevation angle is shown in the third column of the table for the first decoding attempt. It is observed that at elevation angles of 15°, at 52° (which is subject to interference) and from 64° and above, the throughput performance of the existing SR-only protocol is very poor.

It can be concluded that for all elevation angles, the inclusion of the type-II hybrid is a great advantage to the current operating system. Especially is the case for the lower elevation angles of 20° and below, as the satellite passes are more frequent than the higher elevation angles.
5.5. **Performance of the type-II hybrid in OPNET**

In this section, the "real" case simulation of the type-II hybrid in OPNET is evaluated to measure the impact of the actual delays of the packets in propagating through the channel, delays in the decoding and mothercode decoding operations and propagation delays upon the retransmission requests in the feedback channel. Comparisons are made with all results generated from the 4-state and multiple state Fritchman models and measured data.

A novel type-II +delay hybrid is proposed in this section in which a variable time 'delay' is waited before submitting a retransmission request on the feedback channel since the packet was undecodable. The philosophy behind this technique is after a period of time, the conditions of the channel would have improved and sufficient for its repeats to be recovered at the receiver. In this context, the 'delay' parameter will be measured in terms of the number of packets that have arrived at the receiver before a negative acknowledgement is sent for that packet.

In this section, the optimal 'delay' parameter in terms of the number of packets will be derived for the different range of elevation angles through runs with the experimental data and either the 4-state or Fritchman models.

The effects of sizes of the sending and receiving window and consequently the number of buffers to hold the repeats and number of timers are also examined in this section.
The experimental data and the data generated from the corresponding Fritchman model were simulated in OPNET and the throughput performance of the type-II hybrid in terms of the initial decoding process and subsequent mothercode decoding operations was exactly similar to the throughput performance simulations presented and described in Section 5.3.

The performance of the type-II + delay hybrid was then investigated in OPNET with various delay parameters and buffer sizes. It is discovered from the measured data that through a retransmission request at a 'delay' of 3, 4 and 5 packets later, the number of packets utilised for the mothercode operation is reduced when compared to when there was instantaneous request for a retransmission. However, not all the packets are successfully recovered through the mothercode operation. Through further investigations, it is found that with a 'delay' of 6 packets, the number of packets for mothercode operation is less and all packets are successfully recovered. However, with a request of 9 packets later, the number of packets used for the mothercode operation starts to increase again.

Therefore, it is concurred that the optimal parameter for a retransmission request is 6 packets for the experimental data.

<table>
<thead>
<tr>
<th>CODE</th>
<th>DELAY 0</th>
<th>DELAY 3</th>
<th>DELAY 4</th>
<th>DELAY 5</th>
<th>DELAY 6</th>
<th>DELAY 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,32)</td>
<td>0</td>
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<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,64)</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(128,96)</td>
<td>16</td>
<td>12</td>
<td>14</td>
<td>15</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>(128,104)</td>
<td>24</td>
<td>21</td>
<td>22</td>
<td>21</td>
<td>23</td>
<td>16</td>
</tr>
<tr>
<td>(128,112)</td>
<td>53</td>
<td>50</td>
<td>47</td>
<td>41</td>
<td>45</td>
<td>39</td>
</tr>
<tr>
<td>(128,116)</td>
<td>90</td>
<td>75</td>
<td>73</td>
<td>69</td>
<td>74</td>
<td>73</td>
</tr>
<tr>
<td>(128,120)</td>
<td>142</td>
<td>129</td>
<td>119</td>
<td>118</td>
<td>116</td>
<td>121</td>
</tr>
</tbody>
</table>

Table 5-10: The number of packets that pass or fail the mother code operation with variable delays and buffer size of 16 packets for the experimental data at 15°.

Through analysing the data generated from the Fritchman model, it is discovered that when incorporating various 'delay' parameters, the number of packets required for the mothercode operation has reduced compared to zero delays. From Table 5-11, it is deduced that the optimal 'delay' parameter is 5 packets.

<table>
<thead>
<tr>
<th>CODE</th>
<th>DELAY 0</th>
<th>DELAY 3</th>
<th>DELAY 4</th>
<th>DELAY 5</th>
<th>DELAY 6</th>
<th>DELAY 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,64)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,96)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,104)</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(128,112)</td>
<td>37</td>
<td>33</td>
<td>25</td>
<td>33</td>
<td>33</td>
<td>31</td>
</tr>
<tr>
<td>(128,116)</td>
<td>161</td>
<td>129</td>
<td>123</td>
<td>109</td>
<td>134</td>
<td>128</td>
</tr>
<tr>
<td>(128,120)</td>
<td>417</td>
<td>380</td>
<td>378</td>
<td>365</td>
<td>381</td>
<td>386</td>
</tr>
</tbody>
</table>

Table 5-11: The number of packets that pass or fail the mother code operation with variable delays and buffer size of 16 packets for the generated data from the Fritchman model at 15°.
Therefore, from the results simulated for the measured data and Fritchman models, it appears that the technique of variable ‘delay’ parameter is worth considering and the optimal ‘delay’ parameter is either 5 or 6 packets for a satellite pass at 15°.

All results obtained for the type-II and type-II + delay hybrid have been simulated for buffer sizes of 8, 16 and 32. It is demonstrated that all results are consistent for a buffer size of 8, 16 and 32. For all these cases, there are no packets timeouts and packet discards.

5.5.2. From 20°-40° Elevation Angle

At elevation angles of 23°, 30° and 40°, the OPNET simulation has confirmed that the protocols perform as simulated for the experimental and generated data from the 4-state and Fritchman models. The throughput performance of the type-II hybrid remains very high and for each retransmission request, the repeats are recovered all the time. For these range of elevation angles, the OPNET simulation confirms the fact that there is no requirement for the mothercode decoding operation based on simulation runs for the experimental data and the data generated from the Fritchman and 4-state models. Therefore, we concur that there is no need to investigate the optimal ‘delays’ type-II + delay hybrid.

These simulations were repeated for various buffer sizes of 8, 16 and 32. It is discovered that a buffer size of 8 is sufficient to support the operation of the type-II hybrid for these elevation angles. The data generated by both the 4-state model and Fritchman also provide the same results as the experimental data as discussed in Section 5.3.
5.5.3. At 52° Elevation Angle

The type-II hybrid might not be the optimal error control technique to support such circumstances as due to the effects of interference, the bursts are longer and more clustered while the gap lengths reduce considerably. Simulations on the throughput performance of the type-II hybrid have been repeated based on realistic values of propagation and decoding delays and found to be consistent with the results presented in Section 5.3.

In simulating the type-II + delay protocol with the experimental data, it is observed that there is not much improvement in throughput performance of the protocol for various buffer sizes of 8, 16, and 32. This can be attributed to the fact that the range of elevation angles considered (from 48° to 52°) had covered the whole duration of the interference. Naturally, the type-II + delay protocol will not work under such conditions as the channel is always bursty and has not improved for the repeats to be decodable. As displayed in Table 5-12, there is no clear indication of the advantages in variable ‘delays’ in a retransmission request of the type-II + delay hybrid.

<table>
<thead>
<tr>
<th>CODE</th>
<th>DELAY 0 %MC</th>
<th>DELAY 3 %MC</th>
<th>DELAY 6 %MC</th>
<th>DELAY 9 %MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,64)</td>
<td>100</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>(128,96)</td>
<td>90.32</td>
<td>100.00</td>
<td>100.00</td>
<td>100.00</td>
</tr>
<tr>
<td>(128,104)</td>
<td>96.00</td>
<td>97.87</td>
<td>95.74</td>
<td>100.00</td>
</tr>
<tr>
<td>(128,112)</td>
<td>95.71</td>
<td>97.26</td>
<td>95.59</td>
<td>97.14</td>
</tr>
<tr>
<td>(128,116)</td>
<td>95.45</td>
<td>94.51</td>
<td>96.55</td>
<td>97.75</td>
</tr>
<tr>
<td>(128,120)</td>
<td>96.55</td>
<td>96.52</td>
<td>98.23</td>
<td>97.39</td>
</tr>
</tbody>
</table>

Table 5-12: The percentage of packets recovered with the mothercode with variable delays and buffer size of 16 packets for the experimental data at 52°.

Other factors to be seriously considered are the number of packets that timeout or are discarded due to interference. It is found that for a buffer size of 8 packets, when simulating a ‘delay’ parameter of 6 packets for retransmission, there are packets which inevitably timeout and some are discarded, which affects the throughput performance of the protocol as demonstrated in Table 5-13. A practical solution to this problem is to increase the buffer size to 16 packets. As illustrated in Table 5-13, the problems of packet timeouts and discards have been rectified with larger buffer capacity.

<table>
<thead>
<tr>
<th>CODE</th>
<th>BUFFER SIZE 8</th>
<th>BUFFER SIZE 16</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PACKETS TIMEOUT</td>
<td>PACKETS DISCARDED</td>
</tr>
<tr>
<td>(128,96)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,104)</td>
<td>14</td>
<td>1</td>
</tr>
<tr>
<td>(128,112)</td>
<td>16</td>
<td>3</td>
</tr>
<tr>
<td>(128,116)</td>
<td>13</td>
<td>1</td>
</tr>
<tr>
<td>(128,120)</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5-13: The number of packet timeouts and discards for buffer sizes of 8 and 16 and ‘delay’ parameter of 6 packets.
We also examine the long term behaviour of the data generated by the 4-state model since the 4-state model seems to describe the error sequence at 52 degrees more precisely than the Fritchman model. From the results displayed in Table 5-14, it seems that for the data generated from the 4-state model, the repeats are always recovered when they are combined, and none has failed the combined mothercode. For all cases, a buffer size of 8 is sufficient.

<table>
<thead>
<tr>
<th>CODE</th>
<th>DELAY 0</th>
<th>DELAY 3</th>
<th>DELAY 6</th>
<th>DELAY 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,64)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,96)</td>
<td>1728</td>
<td>1306</td>
<td>1276</td>
<td>1296</td>
</tr>
<tr>
<td>(128,104)</td>
<td>4506</td>
<td>3823</td>
<td>3761</td>
<td>3816</td>
</tr>
<tr>
<td>(128,112)</td>
<td>8407</td>
<td>7698</td>
<td>7681</td>
<td>7755</td>
</tr>
<tr>
<td>(128,116)</td>
<td>10763</td>
<td>10025</td>
<td>10059</td>
<td>10100</td>
</tr>
<tr>
<td>(128,120)</td>
<td>13180</td>
<td>12605</td>
<td>12565</td>
<td>12609</td>
</tr>
</tbody>
</table>

Table 5-14: The number of packets recovered with the mothercode with variable delays and buffer size of 16 packets for the Fritchman model at 52°.

### 5.5.4. At 63° Elevation Angle

At a satellite pass of 63°, the performance of the type-II hybrid through OPNET simulation is the same as the results simulated and presented in Section 5.3 for the experimental data and generated data from the Fritchman model. Simulations were performed for various buffer sizes of 8, 16 and 32. It is concurred that a buffer size of 8 is sufficient to store all the necessary repeats for them to be recovered subsequently. Furthermore, it is demonstrated that there is no need for the operation of the mothercode. The results obtained for this elevation angle are similar to that simulated from the 20°-40° range of elevation angles.
5.5.5. At 68° Elevation Angle

At 68°, the experimental data and the data generated from the Fritchman and 4-state models were simulated in OPNET and the throughput performance of the type-II hybrid was as anticipated, from the simulations in Section 5.3.

From simulations with the type-II + delay hybrid, for both cases in the experimental data and generated data from the Fritchman model, the optimal 'delay' parameter is discovered to be 9 packets as depicted in Table 5-15.

<table>
<thead>
<tr>
<th>CODE</th>
<th>DELAY 0 PASS</th>
<th>DELAY 0 FAIL</th>
<th>DELAY 3 PASS</th>
<th>DELAY 3 FAIL</th>
<th>DELAY 4 PASS</th>
<th>DELAY 4 FAIL</th>
<th>DELAY 5 PASS</th>
<th>DELAY 5 FAIL</th>
<th>DELAY 6 PASS</th>
<th>DELAY 6 FAIL</th>
<th>DELAY 9 PASS</th>
<th>DELAY 9 FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,16)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,32)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,64)</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,96)</td>
<td>10</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>(128,104)</td>
<td>18</td>
<td>2</td>
<td>16</td>
<td>2</td>
<td>13</td>
<td>2</td>
<td>12</td>
<td>2</td>
<td>10</td>
<td>2</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>(128,112)</td>
<td>48</td>
<td>3</td>
<td>45</td>
<td>2</td>
<td>44</td>
<td>2</td>
<td>43</td>
<td>2</td>
<td>40</td>
<td>2</td>
<td>37</td>
<td>0</td>
</tr>
<tr>
<td>(128,116)</td>
<td>68</td>
<td>3</td>
<td>63</td>
<td>2</td>
<td>67</td>
<td>2</td>
<td>62</td>
<td>2</td>
<td>59</td>
<td>2</td>
<td>58</td>
<td>0</td>
</tr>
<tr>
<td>(128,120)</td>
<td>107</td>
<td>2</td>
<td>99</td>
<td>3</td>
<td>98</td>
<td>2</td>
<td>91</td>
<td>2</td>
<td>94</td>
<td>2</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5-15: The percentage of packets recovered with the mothercode with variable delays and buffer size of 16 packets for the experimental data at 68°.

Through simulations on the data generated from the corresponding Fritchman model, the optimal 'delay' parameter is also simulated to be 9 packets as the number of packets utilised for the mothercode decoding process has reduced significantly.

<table>
<thead>
<tr>
<th>CODE</th>
<th>DELAY 0 PASS</th>
<th>DELAY 0 FAIL</th>
<th>DELAY 3 PASS</th>
<th>DELAY 3 FAIL</th>
<th>DELAY 4 PASS</th>
<th>DELAY 4 FAIL</th>
<th>DELAY 5 PASS</th>
<th>DELAY 5 FAIL</th>
<th>DELAY 6 PASS</th>
<th>DELAY 6 FAIL</th>
<th>DELAY 9 PASS</th>
<th>DELAY 9 FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,16)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,32)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,64)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,96)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,104)</td>
<td>18</td>
<td>0</td>
<td>12</td>
<td>0</td>
<td>17</td>
<td>0</td>
<td>14</td>
<td>0</td>
<td>19</td>
<td>0</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>(128,112)</td>
<td>246</td>
<td>0</td>
<td>198</td>
<td>0</td>
<td>213</td>
<td>0</td>
<td>201</td>
<td>0</td>
<td>217</td>
<td>0</td>
<td>198</td>
<td>0</td>
</tr>
<tr>
<td>(128,116)</td>
<td>551</td>
<td>0</td>
<td>474</td>
<td>0</td>
<td>492</td>
<td>0</td>
<td>486</td>
<td>0</td>
<td>481</td>
<td>0</td>
<td>491</td>
<td>0</td>
</tr>
<tr>
<td>(128,120)</td>
<td>965</td>
<td>0</td>
<td>893</td>
<td>0</td>
<td>895</td>
<td>0</td>
<td>884</td>
<td>0</td>
<td>891</td>
<td>0</td>
<td>876</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5-16: The percentage of packets recovered with the mothercode with variable delays and buffer size of 16 packets for the Fritchman model at 68°.
5.5.6. At 74° Elevation Angle

The OPNET simulation confirms the performance of the type-II hybrid for the experimental and generated data from the 4-state model. For the experimental data, the investigation of ‘delays’ is difficult for buffer sizes of 8 and 16 packets as there exists numerous timeouts and packet discards as displayed in Table 5-17. For a buffer size of 32 packets, there are no timeouts or discards therefore, we should consider this buffer size to prevent unnecessary packet retransmits.

<table>
<thead>
<tr>
<th>CODE</th>
<th>DELAY 3</th>
<th>DELAY 6</th>
<th>DELAY 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUF 8</td>
<td>BUF 16</td>
<td>BUF 32</td>
<td>BUF 8</td>
</tr>
<tr>
<td>(128,16)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,32)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,64)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,96)</td>
<td>8</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,104)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,112)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,116)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,120)</td>
<td>23</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5-17: The number of packet timeouts for various buffer sizes and delay parameters in a retransmission request for the experimental data at 74°.

<table>
<thead>
<tr>
<th>CODE</th>
<th>DELAY 3</th>
<th>DELAY 6</th>
<th>DELAY 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUF 8</td>
<td>BUF 16</td>
<td>BUF 32</td>
<td>BUF 8</td>
</tr>
<tr>
<td>(128,16)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,32)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,64)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,96)</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,104)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,112)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,116)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,120)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5-18: The number of packet discards for variable buffer sizes and delay parameters in a retransmission request for four-state model at 74°.

Further investigations of the experimental data reveal that at a ‘delay’ of 3 packets, there is in fact a degradation in the mothercode performance. At a ‘delay’ of 6 packets, there is slight improvement and the performance deteriorates at a ‘delay’ of 9 packets as illustrated in Table 5-19.

<table>
<thead>
<tr>
<th>Code</th>
<th>DELAY 0</th>
<th>DELAY 3</th>
<th>DELAY 6</th>
<th>DELAY 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,16)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(128,32)</td>
<td>10.26</td>
<td>12.20</td>
<td>9.76</td>
<td>2.56</td>
</tr>
<tr>
<td>(128,64)</td>
<td>33.82</td>
<td>34.33</td>
<td>31.82</td>
<td>28.13</td>
</tr>
<tr>
<td>(128,96)</td>
<td>31.91</td>
<td>32.98</td>
<td>34.07</td>
<td>35.87</td>
</tr>
<tr>
<td>(128,104)</td>
<td>34.34</td>
<td>34.69</td>
<td>35.05</td>
<td>32.99</td>
</tr>
<tr>
<td>(128,112)</td>
<td>38.39</td>
<td>36.36</td>
<td>39.82</td>
<td>37.84</td>
</tr>
<tr>
<td>(128,116)</td>
<td>41.53</td>
<td>38.46</td>
<td>39.32</td>
<td>39.83</td>
</tr>
<tr>
<td>(128,120)</td>
<td>40.80</td>
<td>42.28</td>
<td>43.55</td>
<td>45.08</td>
</tr>
</tbody>
</table>

Table 5-19: The percentage of packets successfully decoded with the mothercode for a buffer size of 32 packets and variable delay parameters for the experimental data at 74°.

5-23
5.6. **The type-II hybrid for the entire satellite pass**

In this section we investigate the performance of the type-II hybrid for the complete satellite pass ranging from approximately $15^\circ$ to its highest elevation angle of that pass. These simulations were performed using the measured in-orbit data. The throughput performance of the existing SR-ARQ PB protocol is illustrated in Table 5-20. The total throughput performance of the SR protocol is computed as the ratio of the number of error-free packets at the receiver to the sum of all packets sent. From the table, it is observed that the most optimistic achievable throughput of the current system is only 63% for a maximum satellite pass of $40^\circ$ in the best case. For the majority of the range of elevation angles taken into account, the throughput performance of the PB protocol can be as little as 25%.

<table>
<thead>
<tr>
<th>RANGE</th>
<th>PACKETS PASS</th>
<th>PACKETS FAIL</th>
<th>% TOTAL THROUGHPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$15^\circ$ to $23^\circ$</td>
<td>992</td>
<td>580</td>
<td>63.10</td>
</tr>
<tr>
<td>$15^\circ$ to $30^\circ$</td>
<td>473</td>
<td>1360</td>
<td>25.80</td>
</tr>
<tr>
<td>$15^\circ$ to $40^\circ$</td>
<td>1313</td>
<td>751</td>
<td>63.60</td>
</tr>
<tr>
<td>$15^\circ$ to $52^\circ$</td>
<td>893</td>
<td>1350</td>
<td>39.81</td>
</tr>
<tr>
<td>$15^\circ$ to $63^\circ$</td>
<td>826</td>
<td>1008</td>
<td>45.01</td>
</tr>
<tr>
<td>$15^\circ$ to $68^\circ$</td>
<td>825</td>
<td>1204</td>
<td>40.66</td>
</tr>
<tr>
<td>$15^\circ$ to $74^\circ$</td>
<td>759</td>
<td>1314</td>
<td>36.61</td>
</tr>
</tbody>
</table>

Table 5-20: Total throughput of the SR-ARQ PB protocol for a range of elevation angles

The following tables depict the improvement in throughput performance of the PB protocol if the type-II hybrid was utilised for the same range of elevation angles.

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>n</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,96)</td>
<td>3144</td>
<td>0</td>
<td>100</td>
<td>75.0</td>
<td>(128,96)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(128,104)</td>
<td>3143</td>
<td>1</td>
<td>99.97</td>
<td>81.22</td>
<td>(256,104)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(128,112)</td>
<td>3141</td>
<td>3</td>
<td>99.80</td>
<td>87.42</td>
<td>(256,112)</td>
<td>1</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>(128,116)</td>
<td>3138</td>
<td>6</td>
<td>99.81</td>
<td>90.45</td>
<td>(256,116)</td>
<td>1</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>(128,120)</td>
<td>3098</td>
<td>46</td>
<td>98.54</td>
<td>92.38</td>
<td>(256,120)</td>
<td>4</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 5-21: Performance of the type-II hybrid for a satellite pass from $15^\circ$ to $23^\circ$.

From $15^\circ$ to $23^\circ$, it is demonstrated from simulations that the optimal code in terms of efficiency is the (128,120) code which successfully decodes 98.54% of the packets for the first time they are received and with the mothercode decoding operation, 100% of the packets are fully recovered. However, the (128,112) code is a better choice as it provides more reliable decoding than the (128,120) at a slight expense of the protocol efficiency. All the packets are recovered with this code.

For the satellite passes ranging from $15^\circ$ to $30^\circ$, $15^\circ$ to $52^\circ$, $15^\circ$ to $63^\circ$ and from $15^\circ$ to $68^\circ$, the most efficient trade-off between redundancy and the percentage of packets that are successfully decoded is the (128,112) code that recovers at least 78% of the packets. The throughput efficiency is at least 68% and subsequent decoding combinations with the mothercode for all repeat requests give an additional (at least) 94% of the packets which can be recovered.
For a satellite pass with maximum elevation angle of 30°, the achievable throughput efficiency of the type-II hybrid based on a (128,112) code is 68.31% in its first decoding attempt. Out of the number of repeats that were retransmitted, 81.03% were recovered through the (256,112) mothercode decoding operation. In comparison, in the SR PB protocol, the throughput performance is only 25%

| CODE (128,16) | PASS 3606 | FAIL | 0 | %PASS 98.36% | MCODE PASS 1 | FAIL | 23 | %PASS 4.17 |
| (128,32) 3577 | 89 | 97.57% | 24.39% | 6 | 28 | 17.65% |
| (128,64) 3494 | 172 | 95.31% | 47.65% | 24 | 47 | 33.80% |
| (128,96) 3208 | 458 | 87.51% | 65.63% | 133 | 66 | 66.83% |
| (128,104) 3047 | 619 | 83.12% | 67.53% | 209 | 67 | 75.72% |
| (128,112) 2862 | 804 | 78.07% | 68.31% | 299 | 70 | 81.03% |
| (128,116) 2759 | 907 | 75.26% | 38.20% | 339 | 73 | 82.28% |
| (128,120) 2610 | 1056 | 71.19% | 66.75% | 390 | 82 | 82.63% |

Table 5-22: Performance of the type-II hybrid for a satellite pass from 15° to 30°.

At the range of elevation angles from 15° to 40°, similar to the 15° to 23° range, the optimal code in terms of efficiency is the (128,116) code that decodes 96.85% of the packets and recovers a total of 99.82% of all packets with the mothercode operation. However, again the (128,112) code that decodes 97.55% of the packets and recovers 99.83% of all packets with the mothercode is preferred.

| CODE (128,16) 4128 | PASS 0 | FAIL | 100 | %PASS 99.96% | MCODE PASS 0 | FAIL | 0 | - |
| (128,32) 4126 | 2 | 99.95% | 24.99% | 0 | 0 | - |
| (128,64) 4115 | 13 | 99.69% | 49.84% | 1 | 0 | 100 |
| (128,96) 4082 | 46 | 98.89% | 74.16% | 14 | 2 | 87.50 |
| (128,104) 4067 | 61 | 98.52% | 80.05% | 15 | 2 | 88.24 |
| (128,112) 4027 | 101 | 97.55% | 85.36% | 28 | 2 | 93.33 |
| (128,116) 3998 | 130 | 96.85% | 87.77% | 34 | 2 | 94.44 |
| (128,120) 3915 | 213 | 94.84% | 88.91% | 58 | 2 | 96.67 |

Table 5-23: Performance of the type-II hybrid for a satellite pass from 15° to 40°.

For a satellite pass ranging from 15° to 63°, the (128,112) type-II hybrid successfully decodes 86.56% of the packets at its first decoding attempt and 96.97% of repeats through subsequent mothercode decoding. The achievable throughput efficiency is 75.74% compared to 39.81% in the PB protocol.

| CODE (128,16) 4484 | PASS 0 | FAIL | 2 | %PASS 99.96% | MCODE PASS 0 | FAIL | 0 | - |
| (128,32) 4480 | 6 | 99.87% | 24.97% | 0 | 0 | - |
| (128,64) 4458 | 28 | 99.38% | 49.69% | 5 | 2 | 71.43 |
| (128,96) 4306 | 180 | 95.99% | 71.99% | 54 | 5 | 91.53 |
| (128,104) 4153 | 333 | 92.58% | 75.22% | 110 | 9 | 92.44 |
| (128,112) 3883 | 603 | 86.56% | 75.74% | 224 | 7 | 96.97 |
| (128,116) 3663 | 823 | 81.65% | 74.00% | 317 | 9 | 97.24 |
| (128,120) 3372 | 1114 | 75.17% | 70.47% | 447 | 12 | 97.39 |

Table 5-24: Performance of the type-II hybrid for a satellite pass from 15° to 52°.

For a satellite pass ranging from 15° to 63°, the optimal (128,112) code decodes 84.30% of the packets while the (256,112) mothercode decodes 62.7% of the remaining retransmitted packets. Therefore, the
highest percentage of decodable packets is 94%. The throughput efficiency of this type-II protocol is 73.76% compared to the 45% achievable throughput of the PB protocol.

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>η</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,16)</td>
<td>3556</td>
<td>112</td>
<td>96.95</td>
<td>12.12</td>
<td>(256,16)</td>
<td>0</td>
<td>51</td>
<td>0</td>
</tr>
<tr>
<td>(128,32)</td>
<td>3545</td>
<td>123</td>
<td>96.65</td>
<td>24.16</td>
<td>(256,32)</td>
<td>2</td>
<td>54</td>
<td>3.57</td>
</tr>
<tr>
<td>(128,64)</td>
<td>3454</td>
<td>214</td>
<td>94.17</td>
<td>47.08</td>
<td>(256,64)</td>
<td>33</td>
<td>62</td>
<td>34.74</td>
</tr>
<tr>
<td>(128,96)</td>
<td>3335</td>
<td>333</td>
<td>90.92</td>
<td>68.19</td>
<td>(256,96)</td>
<td>66</td>
<td>84</td>
<td>44.00</td>
</tr>
<tr>
<td>(128,104)</td>
<td>3245</td>
<td>423</td>
<td>88.47</td>
<td>71.88</td>
<td>(256,104)</td>
<td>91</td>
<td>90</td>
<td>50.28</td>
</tr>
<tr>
<td>(128,112)</td>
<td>3092</td>
<td>576</td>
<td>84.30</td>
<td>73.76</td>
<td>(256,112)</td>
<td>158</td>
<td>94</td>
<td>62.70</td>
</tr>
<tr>
<td>(128,116)</td>
<td>2968</td>
<td>700</td>
<td>80.92</td>
<td>73.33</td>
<td>(256,116)</td>
<td>213</td>
<td>94</td>
<td>69.38</td>
</tr>
<tr>
<td>(128,120)</td>
<td>2801</td>
<td>867</td>
<td>76.36</td>
<td>71.59</td>
<td>(256,120)</td>
<td>292</td>
<td>99</td>
<td>74.68</td>
</tr>
</tbody>
</table>

Table 5-25: Performance of the type-II hybrid for a satellite pass from 15° to 63°.

Finally, for the higher satellite pass ranging from 15 to 68, the (128,112) type-II hybrid decodes 86.96% of the packets and 69% of the remaining repeats through the (256,112) mother code. In comparison, the PB protocol provides a throughput performance of a mere 36%.

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>η</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,16)</td>
<td>3974</td>
<td>82</td>
<td>97.98</td>
<td>12.23</td>
<td>(256,16)</td>
<td>2</td>
<td>33</td>
<td>5.71</td>
</tr>
<tr>
<td>(128,32)</td>
<td>3954</td>
<td>102</td>
<td>97.49</td>
<td>24.37</td>
<td>(256,32)</td>
<td>4</td>
<td>41</td>
<td>8.89</td>
</tr>
<tr>
<td>(128,64)</td>
<td>3913</td>
<td>143</td>
<td>96.47</td>
<td>48.24</td>
<td>(256,64)</td>
<td>11</td>
<td>50</td>
<td>18.03</td>
</tr>
<tr>
<td>(128,96)</td>
<td>3783</td>
<td>273</td>
<td>93.27</td>
<td>69.95</td>
<td>(256,96)</td>
<td>59</td>
<td>58</td>
<td>50.43</td>
</tr>
<tr>
<td>(128,104)</td>
<td>3681</td>
<td>375</td>
<td>90.75</td>
<td>73.74</td>
<td>(256,104)</td>
<td>94</td>
<td>61</td>
<td>60.65</td>
</tr>
<tr>
<td>(128,112)</td>
<td>3527</td>
<td>529</td>
<td>86.96</td>
<td>76.09</td>
<td>(256,112)</td>
<td>152</td>
<td>68</td>
<td>69.09</td>
</tr>
<tr>
<td>(128,116)</td>
<td>3415</td>
<td>641</td>
<td>84.20</td>
<td>76.30</td>
<td>(256,116)</td>
<td>200</td>
<td>68</td>
<td>74.63</td>
</tr>
<tr>
<td>(128,120)</td>
<td>3214</td>
<td>842</td>
<td>79.24</td>
<td>74.29</td>
<td>(256,120)</td>
<td>284</td>
<td>69</td>
<td>80.45</td>
</tr>
</tbody>
</table>

Table 5-26: Performance of the type-II hybrid for a satellite pass from 15° to 68°.

The multiple decodable packets vs. coding rate plots in Graph 5-9 depict the simulated results that were illustrated in the tables and previously discussed. It is apparent that the type-II hybrid will indeed provide further improvements in the throughput performance of the PB protocol.
5.7. Throughput performance of (64, k) Byte Interleaving

Having thoroughly examined the type-II hybrid, in this section, the effects of block interleaving over several packets are investigated and its performance is compared with the type-II hybrid scheme. For (64, k) block interleaving, 128 codewords are written into an array with each row of the array consisting of one (64, k) codeword. For transmission, the array is read out column by column. At the receiver, the codewords are de-interleaved. Each received 128 codeword is written into all 64 rows of the array and decoded column by column.

Table 5-27 below depicts the simulation results obtained with (64, k) byte interleaving for the experimental data and generated data from the respective 4-state and Fritchman models. This table lists the number of packets that have passed or failed and the percentage of passes for the first decoding process through a (64, k) punctured RS code. The number of subsequent repeats that required the (128, k) mothercode decoding process are also listed.

5.7.1. Performance at 15°

At 15°, a (64, 40) code is able to recover all the received packets for the measured data and data generated from the Fritchman and 4-state models without any need for the operation of the mothercode.

In terms of efficiency, the optimal code for the measured data is the (64, 56) code which recovers 94.89% of the packets at an efficiency of 83% and fully decodes all the packets through the mothercode operation. The same case occurs for the data generated from the 4-state and Fritchman models. The optimal (64, 56) code successfully decodes 99.06% of the packets at an efficiency of 86.7% without any
need for the mothercode operation in the data generated from the 4-state model whilst from the Fritchman model, 97.16% of the packets are decoded at an efficiency of 85%. Subsequent mothercode operation recovers all the remaining retransmitted packets. We therefore can conclude that the Fritchman model and 4-state model can represent the measured statistics with very close result.

5.7.2. Performance at 23°

For elevation angles at 23°, 30° and 40°, a (64,56) code is sufficient to decode all the packets with a 100% success rate for the measured data and the data generated from the 4-state and Fritchman models. At 23°, the (64,56) interleaved code gives 100% packet recovery, the same code manages to decode 99.99% of the packets from the 4-state model and 100% of the packets from the Fritchman model, all at an efficiency of 87.5%. For all of the above cases, there is no need for the mothercode operation. This fact holds for elevation angles of 30° and 40° as well. A simple (64,56) RS code interleaved with the SR-ARQ protocol works perfectly and recovers all packets. It is observed that the data generated from the 4-state model is slightly pessimistic than the actual measured data. It can be deduced that for this range of elevation angles from 23° to 40°, the data generated from the Fritchman model is precise in describing the measured statistics. The data generated from the 4-state model is not as accurate as the Fritchman model, but the results are still very close to the original results.

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
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<td>3840</td>
<td>0</td>
<td>100.00</td>
<td>-</td>
<td>97536</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>9728</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(64,56)</td>
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<td>97350</td>
<td>6</td>
<td>99.99</td>
<td>-</td>
<td>9728</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
</tbody>
</table>
5.7.3. **Performance at 30° and 40°**

For both elevation angles, all packets are successfully decoded with a (64,56) block interleaved technique. For all cases of simulations with the experimental data, Fritchman and 4-state models, there is no requirement for the mothercode decoding operation.
5.7.4. Performance at 52°

At a satellite pass of 52°, investigating the interleaving effects upon the measured data, the tradeoffs between redundancy and decoding success automatically leads to the selection of the (64,40) interleaved code which decodes 97.85% of the packets at an efficiency of 61.16% with no requirement for the mothercode operation. The only code which requires the operation of the mothercode is the (64,56) that recovers 52.93% of the packets at an efficiency of 46.31% and successfully recovers all repeats.

Utilising the same (64,40) interleaving technique, the results from the 4-state model show a 99.94% decoding of packets at an efficiency of 62.5%, which again confirms the fact that there is no need for the mothercode operation. Observing the plots of comparisons between the results of the measured data, 4-state and Fritchman models, we gather that the Fritchman model does not seem to be able to predict the observed statistics as closely as the 4-state model. Nevertheless, the same (64,40) code recovers 99.71% of the packets at an efficiency of 62.3%. For all the three different types of data, i.e. measured data and data generated from the corresponding 4-state and Fritchman models, there is no failure in the decoding process with the mothercode operation.
5.7.5. Performance at 63°

The results obtained for the 63° satellite pass are similar to the results for the 23°-40° range of elevation angles. For all cases, a (64,56) interleaving technique recovers all packets at an efficiency of 87.5% for the measured data and data generated from the 4-state and Fritchman models. Furthermore, there again is no need for the mothercode operation.

5.7.6. Performance at 68°
Table 5-33: (64,k) byte interleaving for a 66° pass

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
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<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(64,32)</td>
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<td>100</td>
<td>-</td>
<td>9728</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>9728</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(64,40)</td>
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<td>9728</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>9728</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
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<td>-</td>
<td>9728</td>
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<td>100</td>
<td>-</td>
<td>9715</td>
<td>13</td>
<td>99.87</td>
<td>-</td>
</tr>
<tr>
<td>(64,56)</td>
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<td>82.81</td>
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<td>9395</td>
<td>333</td>
<td>96.58</td>
<td>60</td>
<td>8548</td>
<td>1180</td>
<td>87.87</td>
<td>68.0</td>
</tr>
</tbody>
</table>

For this elevation angle, a (64,48) code provides very high decoding success of at least 99.69% for the first decoding attempt. All subsequent repeats had not required the mothercode decoding operation.

5.7.7. Performance at 74°

![Graph 5-17: Performance of byte(64,k) interleaving technique for a satellite pass at 74°.](image)

Finally, for a satellite pass at 74°, for the measured data, the percentage of the packets which can be decoded is very low, amounting from 0% to 50.59% of decoding success for the (64,56) and (64,16) interleaving blocks respectively. For the data generated from the 4-state model the number of decoding success range from 0% to 61.19% for the (64,56) and (64,16) interleaving. As for the data generated from the Frtichman model, the decoding success ranges from 0% to 45.26%. The highest achievable efficiency is less than 20% for all the above cases. It is discovered that there the error statistics generated from both the 4-state and Fritchman models can not closely represent the observed statistics.
5.8. **Byte (128,k) interleaving**

In (128,k) block interleaving, 256 codewords are written into an array with each row of the array consisting of one (128,k) code. For transmission, the array is read out column by column. At the receiver, the codewords are de-interleaved. Each received 256 codeword is written into all 128 rows of the array and decoded column by column. The rest of this section describes the simulation results obtained through (128,k) byte interleaving for the experimental data and generated data from the 4-state and Fritchman models. All results are presented in tabular form and graphs, as covered in the previous section.

5.8.1. **Performance of (128,k) Byte Interleaving at 15°**

Table 5-35 below are the results of (128,k) byte interleaving for different code rates for a satellite pass at 15°.

![Graph 5-18: Performance of byte (128,k) interleaving technique for a satellite pass at 15°.](image)

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
</tr>
</thead>
<tbody>
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<td>-</td>
<td>4864</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(128,96)</td>
<td>1536</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>(128,104)</td>
<td>1534</td>
<td>2</td>
<td>99.87</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>100</td>
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<td>4864</td>
<td>0</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
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<td>-</td>
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<td>32</td>
<td>99.34</td>
<td>-</td>
</tr>
<tr>
<td>(128,116)</td>
<td>1402</td>
<td>134</td>
<td>91.28</td>
<td>-</td>
<td>4809</td>
<td>55</td>
<td>98.87</td>
<td>-</td>
<td>4589</td>
<td>375</td>
<td>94.35</td>
<td>4</td>
</tr>
<tr>
<td>(128,120)</td>
<td>1263</td>
<td>273</td>
<td>82.23</td>
<td>10/0</td>
<td>4380</td>
<td>484</td>
<td>90.05</td>
<td>18/0</td>
<td>3600</td>
<td>1264</td>
<td>74.01</td>
<td>13/0</td>
</tr>
</tbody>
</table>

The analysis on the selection of appropriate code rates and hybrid schemes has been performed on the real channel data. At 15°, a (128,120) interleaved code decodes 82.23% of the packets at an efficiency of 77.09% and recovers all subsequent repeats for the experimental data. With the addition of a slight redundancy, no recombination of the mothercode is required. The highest achievable throughput is an efficiency of 85% with a (128,112) code that decodes 97.14% of the packets in the first decoding
attempt at the receiver. Further investigation into the error sequences generated from the 4-state model reveal that the (128,112) interleaved code decodes 99.90% of the packets at an efficiency of 87.41%. As for the Fritchman model, the (128,112) interleaved code decodes 99.34% of packets at an efficiency of 86.92%. For the data generated from the 4-state and Fritchman models, all necessary mothercode operations are a success.

5.8.2. Performance at 23°

![Graph 5-19: Performance of byte (128,k) interleaving for a satellite pass at 23°.](image)

Table 5-36: (128,k) byte interleaving for a 23° pass

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,112)</td>
<td>1792</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
</tr>
<tr>
<td>(128,116)</td>
<td>1792</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4863</td>
<td>1</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
</tr>
<tr>
<td>(128,120)</td>
<td>1791</td>
<td>1</td>
<td>99.94</td>
<td>-</td>
<td>4859</td>
<td>42</td>
<td>99.91</td>
<td>-</td>
<td>4864</td>
<td>0</td>
</tr>
</tbody>
</table>

For elevation angles of 23°, 30° and 40°, the (128,k) interleaved technique performs very well. For these range of elevation angles, no mothercode operation is required for the measured data and data generated from the 4-state and Fritchman models. We have selected the (128,112) interleaved code that decodes 100% of all packets at an efficiency of 87.5%. This is also true for the data from the 4-state and Fritchman models. In addition, it can be concluded that the 4-state and Fritchman models accurately predict the observed error statistics.
5.8.3. Performance at 30° and 40°

Graph 5-20: Performance of byte (128,k) interleaving technique for a satellite pass at 30°.

Graph 5-21: Performance of byte (128,k) interleaving technique for a satellite pass at 40°.

Table 5-37: (128,k) byte interleaving for a 30° elevation pass

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>Mcode</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MC</th>
<th>PASS</th>
<th>FAIL</th>
<th>MCODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,104)</td>
<td>1024</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>48640</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>(128,112)</td>
<td>1024</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>48640</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>(128,116)</td>
<td>1024</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>48640</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>(128,120)</td>
<td>1024</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>48624</td>
<td>16</td>
<td>99.97</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5-38: (128,k) byte interleaving for a 40° pass

<table>
<thead>
<tr>
<th>CODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>%PASS</th>
<th>MCODE</th>
<th>PASS</th>
<th>FAIL</th>
<th>MCODE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(128,104)</td>
<td>1280</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>48640</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>(128,112)</td>
<td>1280</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>48640</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>(128,116)</td>
<td>1280</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>48640</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>(128,120)</td>
<td>1280</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>48640</td>
<td>0</td>
<td>100</td>
<td>-</td>
<td>4864</td>
<td>0</td>
<td>-</td>
</tr>
</tbody>
</table>

At elevation angles of 30° and 40°, the block interleaving performs very well with almost 100% recovery of the packets, with a (128,120) code.
5.8.4. Performance at 52°

At a satellite pass of 52°, the percentage of packets which are decodable is 4.3% for the measured data, 4.98% for the 4-state model and 1.4% for the Fritchman model. A (128,112) interleaved code barely decodes 50% of the packets for these three sets of data. The optimal code for the measured data is (128,96) which decodes 98.44% of packets at an efficiency of 73.83% without the need for mother code combination. Similar to the measured data, the optimal (128,96) code decodes 99.19% of the packets generated from the 4-state model at an efficiency of 74.40% while recovering all retransmitted packets. For the Fritchman model, the optimal (128,96) code decodes 95.15% of packets at a 71.36% efficiency again successfully recovering all repeats. For this elevation angle, the 4-state model can reasonably predict the measured statistics, more accurately than the Fritchman model. Again, it is suspected that the measured channel behaviour can not be described by just one error-state and multiple good states.
5.8.5. Performance at 63°

The analysis on the measured data and generated data from the corresponding 4-state and Fritchman models at a satellite pass of 63°, show similar findings to the results at the 23°, 30° and 40° elevation angles. The interleaved code performs very well and recovers 100% of all packets in its first attempt at decoding without any need for the operation of the mothercode.

5.8.6. Performance at 68°
For a 68° satellite pass, taking into account the tradeoffs required on the measured data, the optimal code seems to be (128, 104) which decodes 99.41% of packets at an efficiency of 80.77% without mothercode combinations. For the 4-state model, less redundancy is required and the optimal code is a (128, 112) which decodes 98.85% of packets at an efficiency of 86.49%. For the Fritchman model, the optimal code is (128, 104) which decodes 99.67% of packets at an efficiency of 80.98%. For all of the above cases, there is no mothercode combination on subsequent retransmitted packets.

5.8.7. Performance at 74°

<table>
<thead>
<tr>
<th>EXPERIMENTAL DATA</th>
<th>DATA FROM 4-STATE</th>
<th>DATA FROM FRITCHMAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>CODE</td>
<td>PASS</td>
<td>FAIL</td>
</tr>
<tr>
<td>(128,80)</td>
<td>512</td>
<td>0</td>
</tr>
<tr>
<td>(128,96)</td>
<td>512</td>
<td>0</td>
</tr>
<tr>
<td>(128,104)</td>
<td>509</td>
<td>3</td>
</tr>
<tr>
<td>(128,112)</td>
<td>466</td>
<td>46</td>
</tr>
<tr>
<td>(128,116)</td>
<td>372</td>
<td>140</td>
</tr>
<tr>
<td>(128,120)</td>
<td>214</td>
<td>298</td>
</tr>
</tbody>
</table>

Graph 5-25: Performance of byte (128,k) for a satellite pass at 74°.
As anticipated for the elevation angle of 74°, much more redundancy is required. Studying the effectiveness of the (128,64) code, the 0.39% of packets are recovered for the measured data, 2.19% of packets are decodable for the 4-state model while 0.04% of packets are decodable for the Fritchman model. For all cases, the highest achievable efficiency is less than 17%. For a (128,16) code, 98.5% of measured data are decodable, while 91.05% and 88.12% of packets are decodable for the data generated from the 4-state and Fritchman models respectively.

5.9. Summary

This chapter has presented all results obtained through simulations on the type-II hybrid, type-II + delay hybrid and block interleaving techniques. The performances of the hybrid protocols and block interleaving were evaluated based on in-orbit data gathered from a LEO satellite and the generated error sequences from the Fritchman and proposed four-state models. These simulations were performed for a wide range of satellite passes. For all elevation angles considered, the type-II hybrid has been shown to provide further improvements in the throughput performance of the existing protocol. The performance of the type-II + delay hybrid is dependent upon the severity of interference experienced in the channel. For the case when the channel is not too bursty, it is possible to derive an optimal 'delay' parameter and would be useful to employ this protocol. However, the effectiveness of the type-II + delay hybrid breaks down during severe interference while increasing the complexity of the existing protocol in terms of buffer sizes for retransmissions and timeouts. Both block (64, k) and (128, k) interleaving are also provide improvements in throughput performance for a range of elevation angles. The (128, k) interleaved technique is shown to decode a large proportion of the packets without much need for the mothercode operation. Further comparisons between the type-II, type-II + delay hybrid, block (64, k) and (128, k) interleaving are made in the next chapter.
Chapter 6

Conclusions and Recommendations for Future Work

6.1. Introduction

This thesis has introduced the current research areas in the efforts of characterising the LEO satellite communications channel and has presented for the first time the fading statistics of the LEO UHF channel through a measurement campaign conducted in Guildford from a LEO microsatellite. It has investigated the suitability of various generative models in the attempt to characterise the observed channel fading statistics. It has analysed how closely the generative models predict the observed statistics of the measured data and proposed two models consisting of multiple-state Markov models to represent the LEO satellite channel under special circumstances. It has evaluated the performance of two different error control strategies, namely the type-II hybrid and block interleaving to be incorporated with the existing operating suite of PACSAT protocols. Through extensive simulations, the tradeoffs that need to be weighed when making the choice in selecting between the two schemes are identified. A novel type-II + variable delay protocol was proposed and has been demonstrated to provide further improvements. The throughput performance of the current SR ARQ system has been evaluated and shown that both proposed error control strategies will indeed provide some improvement towards the throughput efficiency of the protocol. This final chapter summarises all important major findings that were covered in the previous sections, presents and compares between the different error control techniques and states the significant results achieved in this thesis. In particular, the novelties encountered during the course of this study will be highlighted.
To ensure continuity of this research, a few recommendations are made in the second half of this chapter regarding the types of channel characterisation programs that can be conducted and other types of hybrid-ARQ schemes that are worth pursuing in the future.

6.2. **LEO UHF Channel Measurements and Characterisation**

In the process of characterising the LEO UHF satellite communications channel, the fleet of fourteen SSTL microsatellites in LEO seemed to provide ample opportunity to gather proper and real in-orbit measurements, however, almost all the microsatellites could not be dedicated towards the sole purpose of a full-time measurement campaign. Fortunately, the failure of the On-board Computer (OBC) on the UoSAT-3 micro satellite had provided the chance to gather some real in-orbit LEO data.

6.2.1. **Method of Measurement**

The measurement setup was relatively straightforward and simple. The sets of data were gathered for whole satellite passes ranging from initial acquisition of signal from the satellite, to the maximum elevation angle of the satellite pass to loss of signal for multiple satellite passes. Each data set consisted of 150-180 Mbytes of data per satellite pass and the repeatability of the measurements over several passes verifies that the data is valid.

The decision to model the LEO UHF satellite channel steered towards characterising the hard decisions of error sequences, which was dictated by the lack of soft-decision information from the demodulator of the current hardware. The method employed in analysing the data in terms of burst lengths and burst gaps based on a pre-selected threshold density has been accepted and utilised by many.

6.2.2. **Error statistics of the LEO UHF satellite channel**

The results of the error sequences of the LEO UHF channel were categorised into three ranges of elevation angles corresponding to the satellite passes - from 15° and below, from 20° to 63°, and from 70° to nearly 90°. At a satellite pass of 10°, reliable communications is virtually impossible as the average bit error rate is in the order of 10^-2 and 95% of the gap lengths are less than 100 bits.

At a satellite pass of 15°, the communications conditions of the link improves considerably due to less multipath degradation. As the elevation angles increases the link is less bursty as demonstrated in the burst statistics for the 20° to 63° satellite passes. It is concurred that without the effects of unpredictable interference, the bursts encountered for the 20° to 63° range of elevation angles can be treated as AWGN as the bursts are random and 90% of the burst lengths are in the order of 5 bits or less. The effects of ionospheric scintillation are observed in the LEO UHF link for this range of elevation angles as shown from the burst statistics. It also confirms the statement in Chapter 2 that the observable effects of ionospheric scintillation upon a system can be considered as AWGN. Moreover,
from the error statistics, it is shown that reliable communications is achievable with a LEO satellite for these elevation angles.

On the other hand, the effects of interference can be experienced at any elevation angle of the satellite pass and are totally unpredictable as demonstrated for a satellite pass at 52°. The devastating effects of interference were proven from the computed average BER of $10^{-2}$ in the channel for the 48° to 52° range of elevation angle that covers the whole duration of the interference. It is observed that there can be a total communications breakdown with the LEO satellite due to interference.

For the satellite passes at the higher elevation angles from 70° to nearly 90°, the bursts experienced are not random but demonstrate a clustering effect which can be attributed to the inefficient design of the satellite antenna. It is suspected that the current design of the satellite antenna, with a 20 dB null at zenith to compensate for the variations in FSL in the link, is non-optimal for these high elevation angle satellite passes. Generally, as the elevation angle increases, the conditions of the link should automatically improve and one would anticipate nearly AWGN conditions. However, the actual error sequences experienced are drastic and very similar to the bursts experienced at a satellite pass at 10°.

In summary, based on the above discussions, the results obtained for the LEO UHF channel have shown a dependency on the elevation angle of the satellite pass, a strong correlation with the effects of multipath phenomena as demonstrated at the low elevation angles and degradation by the unpredictable effects of interference.

6.2.3. The Fritchman model

Thorough analysis of the error statistics has shown that the simplest Markov models, such as the Gilbert or Elliott model, cannot adequately represent the measured error statistics of the LEO UHF satellite channel for all elevation angles considered. The error processes are more complex than that described by a one-good state one-error state.

However, this research has revealed that for a satellite pass from 15° to 68°, a one-error state and two or three-good state Fritchman model can accurately represent the measured error statistics under instances when there is no interference. It is therefore possible to estimate Fritchman's model parameters from the measured data and derive the corresponding transition probabilities of the Fritchman model. This also shows that the error-free run distribution can be described by the sum of exponential functions which can be utilised for the derivation of the corresponding transition probabilities. Furthermore, it is found that the curve-fitting procedure to the error-free run distribution is sufficient to provide good fits to the measured data.

The results obtained have been verified through plots of the cumulative histograms of the burst lengths and gaps and comparisons with the measured data. These results are further evaluated based on the performance of the measured statistics and those generated from the Fritchman model through error-control strategies detailed in Chapter 5, thereby verifying the preciseness of the model.
However, in the event of unpredictable interference, the one-error state multiple good-state Fritchman model can not describe the error sequences as accurately, despite the fact that there is a close fit in the cumulative bursts and gaps histograms produced by the Fritchman model to the measured. It is therefore suspected that the error burst process produced by interference can not be represented by one error state.

In general, it is discovered that it is possible to construct a digital channel simulator for a one-error state and two- or three-good state Fritchman model for the LEO UHF channel, whose corresponding transition probabilities are derived from the measured data. This simulator can accurately represent the measured error sequences for the range of elevation angles from 15° to 68°. When interference is experienced, this model fails.

6.2.4. The four-state Markov model

The four-state Markov model, based on two good states and two error states has been proposed to analyse instances in which interference is experienced on the LEO UHF channel and to represent the clustering effect at very high elevation angles.

The process of deriving the corresponding transition probabilities of the 4-state model has been tedious due to the following deficiencies. There are uncertainties in the probabilities of error in the good state, therefore the figure of 0.4 was assumed as the probability of an error occurring while in the good state through rough eye estimation. Due to lack of insufficient data and unfamiliarity with the subject, it was difficult to obtain the actual transition probabilities between each of the states.

It is concluded from the research that the 4-state Markov model can provide reasonable estimations of the original measured data. The eminence of this model over the Fritchman model occurs when there is a need to model the effects of interference and clustering effects at the very high elevation angles.

6.3. Protocol Performance

It was unknown until now how much improvement is actually achievable through the introduction of a hybrid-ARQ scheme on the existing PACSAT protocols. The simulations performed in this research have illustrated that improvements are achievable with three different error control strategies.

For simulations based on the PB protocol, it was assumed that the LEO feedback channel is error-free and that all requests for packet retransmission and acknowledgements that the previous received packet was decodable were always received by the satellite on the feedback channel. This assumption may not hold in the real case. For elevation angles from 23° to 63°, the LEO UHF channel statistics do not exhibit a high level of burstiness and one would assume that the feedback channel is the same bursty conditions as the forward channel. However, for satellite passes for 15° and below and those above 68°, the burst effects on the feedback channel could be significant.
6.4. Error Control Techniques

The objectives outlined at the start of this research in investigating the performance of various error-control strategies and identifying the tradeoffs between them have been achieved. The conclusions drawn for different elevation angles of the LEO UHF satellite pass based on simulations with the type-II hybrid, type-II + delay hybrid and block interleaving are presented as follows.

6.4.1. A satellite pass at 15°

For a satellite pass at 15°, after weighing tradeoffs between efficiency, the number of decodable packets and decoding reliability, the optimal code is a (128,112) RS code in the type-II hybrid configuration. This code recovers 90.88% of packets for the first decoding attempt at the receiver and subsequent 96% of the repeats through the mothercode decoding operation. Further improvements are attainable through the type-II + delay hybrid that recovers all packets through incorporating a delay parameter of five or six packets before submission of a NAK, as verified from the experimental data and corresponding Fritchman model. For both the type-II and type-II + delay schemes, it is also discovered that a receiving window of eight packets is sufficient to cover the operation.

As for (64,k) block interleaving, the (64,56) code decodes 94.89% of the packets and successfully recovers all subsequent retransmitted packets with the mothercode. In comparison, the (128,112) block interleaved code decodes 97.14% of the packets without the need to utilise the mothercode decoding. Based on the above comparisons, it is concluded that block interleaving with a RS (128,112) code is the optimal strategy for a satellite pass at 15° as the achievable throughput performed is higher and the technique provides the same amount of reliability in decoding as the (128,112) code in the type-II configuration. Moreover, all subsequent repeats are guaranteed to be recovered. However the delays involved in the interleaving process have to be taken into account.

6.4.2. For satellite passes at 23°, 30° and 40°

For these range of elevation angles, comparisons between the type-II, type-II + delay hybrid and interleaving techniques have been made. In the type-II configuration, the optimal (128,112) RS code recovers 100% of all packets for a satellite pass at 20°, 99.64% of packets at 30° and 99.93% of packets at 40°. For all the cases, the mothercode decoding operation is not utilised at all. Needless to say, it is implied that the type-II + delay protocol is not essential for the above scenarios. As for block (64,56) interleaving, all packets are decoded with a 100% success rate without any need for the mothercode decoding operation. Similarly, for (128,112) block interleaving, it is demonstrated that all packets are successfully recovered without requiring mothercode decoding operations. Therefore, a choice exists in selecting either a (128,112) RS code with ARQ with slight tolerance to the retransmission requests, or the (128,112) byte interleaved code with degradation in delay.
6.4.3. A satellite pass experiencing interference at 52°

At 52°, the optimal choice is a (128,96) RS code in the type-II hybrid that decodes 79.46% of packets for its first decoding attempt and recovers 90.32% of the repeats through the mothercode. However, this scheme is subject to multiple retransmissions. To ensure a 100% success in the decoding process, a (128,64) RS code will fulfil the specifications at the expense of slight increase in redundancy. For the type-II + delay hybrid, it is confirmed from simulations that the protocol is dependent upon the duration of the interference experienced on the channel. It is obvious that by considering the range of satellite passes from 48° to 52° which cover the entire duration of the interference, the type-II + delay protocol does not provide any improvements in performance as the repeats are sent when the channel has not improved.

Moreover, it is found that the effects of interference impact upon the size of the receiving window and thus the number of packets that will timeout or will be discarded.

For block interleaving, the optimal (64,40) RS code recovers 97.58% of packets and all repeats are subsequently recovered without the need for the mothercode decoding operation. The optimal (128,96) interleaved code appears to be the best choice that decodes 98.44% of the packets, repeatedly without need for the mothercode. Possibly, in this case with interference, the best choice between the three schemes is block interleaving with a (128,96) RS code.

6.4.4. A satellite pass at 63°

For a satellite pass at a maximum elevation angle of 63°, it is confirmed through simulations that the types of error control techniques worth taking into consideration are similar to the schemes suggested for the 23°, 30° and 40° satellite passes. In the type-II configuration, the optimal (128,112) RS code seems to recover 100% of all packets without the mothercode decoding operation. Needless to say, it is implied from this results that the type-II + delay protocol is not required. As for block (64,56) interleaving, all packets are decoded with a 100% success rate without any need for the mothercode decoding operation. Similarly, for (128,112) block interleaving, it is demonstrated that all packets are successfully recovered without requiring mothercode decoding operations. Therefore, a choice exists in selecting either a (128,112) RS code with ARQ with slight tolerance to the retransmission requests, or the (128,112) byte interleaved code with degradation in delay.

6.4.5. A satellite pass at 68°

In a type-II hybrid configuration, it is discovered that the optimal code is a (128,104) that decodes 89.88% of the packets and that recovers 90% of the repeats with mothercode decoding operations. As for the type-II + delay protocol, the optimal “delay” parameter has been simulated to be nine packets based on analysis with both the measured data and data generated from the Fritchman model. With a delay parameter of nine packets, all repeats can be recovered.
On the other hand, a (64,40) block interleaved code successfully recovers all packets the first time without utilising the mothercode. An interleaved (128,104) code decodes 99.41% of all packets, again without requiring mothercode decoding operations. It seems that for this elevation angle block interleaving is preferable to the type-II hybrid scheme.

6.4.6. A satellite pass at 74° and higher elevation angle passes

For these satellite passes, in the type-II hybrid configuration, the optimal (128,64) RS code decodes only 44.27% of the packets and recovers a third of the repeats through subsequent mothercode decoding operations. For the type-II + delay scheme, a delay parameter of six packets seem to provide slight improvement in performance of the mothercode decoding. An extra 5% of the repeats are recovered from the original one-third of success in the type-II hybrid. It is discovered that receiving windows of 8 and 16 are not sufficient to support the retransmission and buffering requirements. It is shown that there were many packets that have timeout or were discarded with these window sizes. However, there are no packet timeouts or discards for a receiving window of 32 packets. For (64,k) block interleaving, the highest achievable efficiency is less than 20% for a (64,16) code. In (128,k) block interleaving, the highest achievable efficiency is less than 17%. For this elevation angle, all three schemes do not provide much improvements.

6.4.7. Final Remarks

Given that a wide range of channel conditions were experienced for many different elevation angles, comparing all results of the simulations with satellites passes from 15° to 63°, it is quite evident that block interleaving with the (128,112) code yields much better improvements than the type-II hybrid, and in some of the cases, the operation of the mothercode decoding is not required at all. The worst conditions of the link occurs at satellites passes of 68° and above, and more careful design will be required from the satellite antenna. However, the problem might not be quite as serious as the majority of the satellite passes occurs at the lower elevation angles, i.e. 22% of the available communications time is spent at elevation angles greater than 20 degrees.
6.5. **Future Work in Channel Measurements and Error Control Techniques**

In terms of applicability, the research performed and presented in this thesis can be utilised for future simulation, design and proper planning of networks and constellations of satellites in LEO.

Future channel modelling techniques need to provide analogue noise representation in the output of the demodulator. The solution adopted in this research was, however, constrained due to the lack of soft decision demodulation. Assuming that soft decisions could be provided, the future areas for continuing research and development in field of error control techniques for LEO satellites are outlined as follows.

6.5.1. **Future LEO Measurement Campaign**

The research covered in this thesis has paved the very first steps towards creating a complete database of the LEO channel fading statistics that can be extended for different environments, frequency of operation and various types of satellite and groundstation antennae.

The measurement campaign was constrained to the environment in Guildford, Surrey, which can be classified as a suburban area. It is a well known fact that the channel fading statistics are affected by the surrounding terrain configuration and existence of any scatterers. Therefore, more scope is required to conduct a series of measurements from different environment that include urban, suburban, wooded and rural areas.

The measurement campaign was confined to the 435 MHz UHF frequency band which was employed on the downlink of the SSTL LEO microsatellites. As the trend of the space industry is steering towards the higher frequency bands, there will be a requirement to extend the database of the LEO fading statistics for other frequency bands. With the recent launch of UoSAT-12 minisatellite (April 1999) that supports L and S-band, further results can be obtained for these frequency bands and compared with the fading statistics in the UHF bands.

Furthermore, the antenna used during the measurement campaign is a UHF groundstation high gain 15.5 dBi tracking helix antenna and there is interest towards the statistics obtained for other types of antennas. If future S-band measurements from the UoSAT-12 minisatellite in LEO are desired, the existing 2m dish used for the UoSAT-12 S-band link can be utilised.

6.5.2. **Hybrid-ARQ based on convolutional codes**

The approach to convolutional codes is substantially different from that of RS codes. This is because the development and analysis of block codes have been based on algebraic/combinatorial techniques, while good convolutional codes have been designed based on extensive computer searches for the best code distance properties. Convolutional codes are conventionally used for AWGN channels and where the data is structured as a continuous stream, however, they may also be used as burst-error correction codes.
A convolutional code has the merits of simplicity of implementation, costs less than a block encoder and in conjunction with Viterbi decoding, it can offer soft-decision decoding with little increase in complexity.

Convolutional codes can be used in hybrid-ARQ protocols through the modification of standard FEC decoders. In this configuration, a source of reliability information within the decoding algorithm can be identified and used to estimate the reliability of decoded data packets. If a decoded packet is deemed unreliable, a retransmission is requested; otherwise, the packet is accepted and passed along to the data sink. This approach has been successfully applied to sequential decoding algorithms by Drukarev and Costello [Drukarev83], and to the Viterbi algorithm by Yamamoto and Itoh [Yam80] and Wicker [Wicker88]. Convolutional codes can also be incorporated into code combining schemes [Chase86].

Among the convolutional code based hybrid schemes, an alternate parity-data retransmission type-II ARQ hybrid can be incorporated with a rate-1/2 convolutional code using either Viterbi or majority-logic decoding. In this scheme, an \((n,k)\) block code detects the errors while the error-correcting code is represented by a half-rate \((2,1,m)\) convolutional code with memory order \(m\). This scheme (using Viterbi decoding) has been shown to provide significantly better throughput performance than pure SR-ARQ with infinite receiver buffers when the channel bit error rate is high.

Lugand and Costello proposed a scheme that utilises an error detecting \((n,k)\) block code but employed in conjunction with a higher-rate \((3,2,m)\) convolutional error-correcting code [Lugand82].

### 6.5.3. Hybrid-ARQ based on Sequential decoding

Although Viterbi decoding is usually used for convolutional codes, the first practical decoding algorithm for convolutional codes was described in 1961 by Wozencraft and Reiffen. This algorithm was the first of a class of sequential algorithms that provide fast but sub-optimal decoding for convolutional codes.

The sequential decoder provides dramatic improvements in computational complexity and therefore long constraint lengths can be used. The decoder is usually not incorporated with soft decision.

Two schemes for use in packet switching networks which make use of convolutional codes with sequential decoding have been investigated in type-I hybrids. They are the Time-Out Algorithm (TOA) and the Slope Control Algorithm (SCA). In the time-out algorithm, if the decoding process is not completed within the specified time, i.e. the time-out limit is exceeded, a retransmission is requested. On the other hand, SCA can recognise a noisy received sequence as soon as erroneous bits are processed by the decoder, rather than waiting for the time-out limit to be exceeded. The SCA monitors the metric of the best path in a sequential decoder. When the slope of this metric becomes too negative, that is, the metric of the best path is decreasing too rapidly, decoding comes to a halt and a retransmission is requested. By comparison, the throughput of SCA is higher than TOA.
Kallel considered sequential decoding with ARQ and code combining under the timeout condition [Kallel88]. Whenever the decoding time of a given packet exceeds some predetermined duration, decoding is stopped and retransmission of the packet is requested. However, the unsuccessful packets are not discarded, but are combined with their retransmitted copies. It was shown that code combining allows sequential decoding to operate efficiently and the use of code combining yields a significant throughput even at very high channel error rates, thus making the system very robust under severe channel degradation.

### 6.5.4. Hybrid-ARQ with Diversity Combining

An averaged diversity combining technique can be based on rate-compatible punctured convolutional codes and the Yamamoto-Itoh (YM) decoding algorithm [Wicker88]. In the average combining technique, suppose that $L$ copies of a packet have been received. The $L$ packets are combined into a single packet of the same length by averaging the soft decision values of the copies of each code word co-ordinate.

In the YM decoding algorithm, the surviving path and the best non-surviving path are compared at each node at each stage in the decoding process. If the difference in the path metrics of the two paths falls below a threshold $u$, then the survivor is declared unreliable. If all paths are declared unreliable before decoding is completed, then a retransmission request is generated.

Error detection in this system is provided by residual redundancy in the convolutional code or by a CRC code. A simple averaging circuit is all that is needed to convert a soft-decision Viterbi decoder into a diversity combining decoder.

### 6.5.5. Majority-logic decoding

Both block and convolutional majority-logic decoders have been modified for use in type-I protocols in the mobile environment [Wicker1,2]. The merits of the majority-logic decoder are that majority-logic techniques are simple to implement, the decoder implementation is easier than the Viterbi or sequential decoder. The decoder can be used with both block and convolutional codes. The use of majority-logic decoding provides moderate values of 1-3dB coding gain. It is capable of higher speed operations than the Viterbi or sequential decoders and attractive in low-cost applications due to its modest implementation.

On the other hand, its disadvantage is that it cannot be used with any arbitrary convolutional codes; even so, the codes that can be used do not have good distance properties.
6.5.6. Hybrid-ARQ based on Turbo Codes

Turbo codes were proposed by Berrou et al. in 1993 and are powerful error correcting codes that approach the Shannon Limit. They use a parallel concatenation of recursive systematic convolutional codes and they require an iterative decoding technique [Berrou93]. Several versions of hybrid-ARQ schemes based on Turbo Codes have been proposed. One such technique uses the log-likelihood ratios generated by the decoder during a previous transmission as a priori information when decoding retransmissions [Stuber97]. Another technique include generating a list of probable paths at the Turbo decoder output and using a CRC check to make the final path selection. A different approach proposes the use of additional pseudo-random interleavers during packet retransmissions. Another combination proposed the use of two modes of operation. For the first transmission, the conventional uncoded ARQ mode is utilised, with a Turbo coded ARQ mode is used for subsequent retransmissions. In all of the above schemes, further improvements were achieved.
6.6. **Implementation and in-orbit demonstration**

The future procedure of implementation and in-orbit demonstration in a LEO microsatellite based on the existing SSTL system is outlined as follows. The AX.25 server task (QAX25) on board the spacecraft is available for the Spacecraft Operating System (SCOS). The sequence of data transmission is as follows. Before an application task can receive or transmit any AX.25 data, it must register its AX.25 address with the QAX25 server. Once the application has registered, QAX25 will notify it of any incoming requests for that address. If the application accepts a request, a connection is established and data can be transmitted and received over the circuit. The complexities of data transfer are hidden from the application by the server, and the application can assume that the circuit is error-free.

![AX.25 TNC](image)

**Figure 6-1: Satellite and ground station AX.25 servers**

The process of developing the software, from the completed source list in the simulation phase to implementation on the microsatellite is described in this subsection. The Spacecraft Operating System SCOS from BekTek (a company that specialises in writing software for microsatellites) also supplies a server task that implements the AX.25 protocol. SCOS supports the C programming language, and permits programmers to use standard, well-supported Microsoft C development tools operating under MS-DOS. Programmers can edit, compile and initially debug their programs on a standard IBM PC or compatible computer using the full range of debugging tools provided by Microsoft. In such a familiar environment with rich compile-time error checking and source-code debugging, programmers produce reliable software rapidly.

Program testing is also an important consideration for spacecraft software. Although the SSTL bus is designed specifically so that failed software will not cause mission failure, extensive testing is still desirable. SCOS supports three phases of software testing: MS-DOS, OBC emulator and spacecraft engineering model. Initially, algorithms destined for SCOS tasks can be compiled and linked to run under MS-DOS. In some cases, the programmer must provide replacements for SCOS-specific functions, but these often represent only a small portion of the programming task. Using top down testing, many tasks can be fully tested under MS-DOS.

When it becomes necessary to test the program under SCOS, a standard IBM 80186 Real-time Interface Co-processor card (RIC) provides a high-fidelity OBC emulator. The RIC, installed in the developer’s PC, runs the SCOS kernel, Bektek I/O drivers and AX.25 server task. Applications running on the RIC under SCOS can be extensively monitored from the PC by MS-DOS programs using a shared address...
window into the RIC memory space. Variables can be displayed or altered, O/S resources can be checked and inter-task communication messages can be captured.

After being tested under SCOS on the RIC, the software can be re-linked to operate on the satellite Engineering Model (EM). The EM provides the ultimate in fidelity being virtually identical to the orbiting satellite - but it is nowhere near as responsive a debugging environment as DOS or the RIC. By the time that programs are run on the EM, they should be mostly debugged, and the EM tests act as a final stage of qualification before programs are executed on the satellite in orbit.

6.7. **Final Remarks**

The novelties of the research during the course of the study are as follows:

- Using in-orbit measurements from a satellite in LEO, the proposed one-error state multiple-good state Fritchman generative model can provide accurate results in terms of modelling the error sequences for a range of elevation angles.

- Given a wide range of varying channel conditions, the optimal coding scheme to be utilised for the LEO UHF channel has been identified.

- The burst error statistics and gap statistics of the LEO UHF satellite channel are presented for the first time.

- These results have shown a dependency on elevation angle, on the design of the current system and on the occurrence of unpredictable interference.

- A reasonable approximation when modelling instances of interference or clusters of errors which are not random and system dependent is obtained through a two-good state two-error state proposed Markov model.

- A novel type-II + delay hybrid is proposed and shown to provide improvements in throughput performance.

- The type-II hybrid based on punctured Reed Solomon codes and mothercode combining has demonstrated to provide increases the throughput performance of the current PB protocol.

- Further improvements available through block interleaving have been identified.

Finally, future work for soft decision channel characterisation, appropriate ARQ schemes and system implementation have been proposed.
The results of the research have been published in the following conferences:


6.8. References


