SCSH/NI: A MAC Protocol for Implanted Telemetry

by

ROBERT WILLIAM VIRTUE

B.A.Sc. The University of British Columbia, 2003

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF APPLIED SCIENCE
in
THE FACULTY OF GRADUATE STUDIES

[ELECTRICAL & COMPUTER ENGINEERING]

THE UNIVERSITY OF BRITISH COLUMBIA

August 2005

© Robert William Virtue, 2005
ABSTRACT

Small wireless devices face resource constraints that demand compromises between operational range, longevity and data traffic. Reduced device dimensions significantly impact antenna efficiency and the power capacity of primary cells.

When such a device is implanted under the skin of a young animal, additional difficulties arise as a result of the losses and detuning effects of the growing tissues. The species targeted by this research project inhabit an environment characterized by rocky formations and salt water, further hampering radio frequency communications. Physical layer design and Medium Access Control (MAC) protocols must work together to provide adequate performance of the system as a whole.

Herein the Single Channel Sharing Hybrid (SCSH) MAC protocol is developed. SCSH provides both range and longevity by exploiting the low data transfer requirements of the application and an environment that allows the use of a Master/Slave star network topology. After a critical review of several possible designs, the SCSH MAC was selected as providing the best system performance while achieving the tag longevity goal of three years, maximizing communications range and minimizing interrogator costs.

The SCSH MAC features scalability to handle an arbitrary number of tags, exploits low data rates and reporting frequencies to minimize collisions and provides a mechanism for eliminating redundant transmissions following a collision or otherwise corrupted transmission. The protocol provides the practical illusion of always-on tag operation, allowing for on-demand surveys and mitigation of fading effects while simultaneously ensuring tag longevity goals are met.

The Single Channel Sharing Hybrid with Networked Interrogators (SCSH/NI) architecture consists of a self-organizing network of small, inexpensive interrogators that communicate with tags using the SCSH protocol. SCSH/NI interrogators enable coverage of complex geographies and ensure functionality for short-range communications.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>vi</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF ACRONYMS</td>
<td>ix</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENT</td>
<td>xii</td>
</tr>
<tr>
<td>CHAPTER 1 Introduction and General Background</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Telemetry Systems</td>
<td>5</td>
</tr>
<tr>
<td>1.2 Wildlife Telemetry</td>
<td>7</td>
</tr>
<tr>
<td>1.2.1 Radio Techniques</td>
<td>7</td>
</tr>
<tr>
<td>1.2.2 Attachment Techniques</td>
<td>8</td>
</tr>
<tr>
<td>1.3 Marine Mammal Application</td>
<td>9</td>
</tr>
<tr>
<td>1.3.1 Longevity</td>
<td>10</td>
</tr>
<tr>
<td>1.3.2 Range</td>
<td>11</td>
</tr>
<tr>
<td>1.3.3 Thesis Objective and Outline</td>
<td>15</td>
</tr>
<tr>
<td>CHAPTER 2 Medium Access Control Layer</td>
<td>17</td>
</tr>
<tr>
<td>2.1 Open Systems Interconnection Reference Model</td>
<td>17</td>
</tr>
<tr>
<td>2.2 Multiplexed Collision Avoidance</td>
<td>20</td>
</tr>
<tr>
<td>2.2.1 Contention-based</td>
<td>21</td>
</tr>
<tr>
<td>2.2.1.1 ALOHA</td>
<td>21</td>
</tr>
<tr>
<td>2.2.1.2 SCADA</td>
<td>22</td>
</tr>
<tr>
<td>2.2.1.3 Carrier Sense Multiple Access (CSMA)</td>
<td>23</td>
</tr>
<tr>
<td>2.2.2 FDMA</td>
<td>23</td>
</tr>
<tr>
<td>2.2.3 Spread Spectrum</td>
<td>23</td>
</tr>
<tr>
<td>2.2.4 TDMA</td>
<td>25</td>
</tr>
<tr>
<td>2.2.4.1 Polling</td>
<td>25</td>
</tr>
<tr>
<td>2.3 Sensor Networks</td>
<td>26</td>
</tr>
<tr>
<td>2.4 Conclusion</td>
<td>28</td>
</tr>
<tr>
<td>CHAPTER 3 Physical Layer</td>
<td>29</td>
</tr>
<tr>
<td>3.1 Physical Layer Goals</td>
<td>30</td>
</tr>
<tr>
<td>3.1.2 Information Transfer Requirements</td>
<td>30</td>
</tr>
<tr>
<td>3.1.2.1 Locale</td>
<td>30</td>
</tr>
<tr>
<td>3.1.2.2 Information Rate</td>
<td>31</td>
</tr>
<tr>
<td>3.1.2.3 Additional Information Transfer</td>
<td>32</td>
</tr>
<tr>
<td>3.2 Antennas</td>
<td>33</td>
</tr>
<tr>
<td>3.2.1 Resonance and Superstrates</td>
<td>33</td>
</tr>
<tr>
<td>3.2.2 Tissue Issues</td>
<td>35</td>
</tr>
<tr>
<td>3.2.3 Miniature Antennas</td>
<td>38</td>
</tr>
<tr>
<td>3.3 Power</td>
<td>39</td>
</tr>
<tr>
<td>3.3.1 Efficiency Metric</td>
<td>39</td>
</tr>
<tr>
<td>3.3.2 Duty Cycle</td>
<td>40</td>
</tr>
<tr>
<td>3.3.3 Batteries</td>
<td>41</td>
</tr>
</tbody>
</table>
3.3.3.2 Shunt Capacitor Bank ........................................ 43
3.3.3.3 Switched Capacitor Bank .................................... 44
3.3.4 Scavenged Power ........................................... 46
  3.3.4.1 Temperature Gradients .................................. 46
  3.3.4.2 Pressure Gradients ...................................... 47
  3.3.4.3 Vibrations .............................................. 47
3.4 Summary .................................................................. 48
CHAPTER 4 Architecture Alternatives ................................. 49
4.1 Frequency Selection ............................................. 50
  4.1.1 ISM Bands ...................................................... 50
  4.1.2 Unlicensed Operation ........................................ 51
4.2 Medium Access Protocol Design ................................. 53
  4.2.1 Network Topology ............................................ 53
  4.2.2 Contention-Based ............................................ 55
4.3 Blind Transmit ..................................................... 55
  4.3.1 Spread Spectrum .............................................. 56
  4.3.2 Pulsed Carrier ................................................ 56
  4.3.3 Mitigating Collisions ....................................... 57
  4.3.4 More PHY Layer .............................................. 57
  4.3.5 Summary ...................................................... 58
4.4 Pulse Triggering ................................................... 59
  4.4.1 Passive Detector ............................................. 60
  4.4.2 Cycled Active Detector ..................................... 63
    4.4.2.1 Scalability ............................................. 66
  4.4.3 Contention Summary ....................................... 69
4.5 Single Channel Sharing Hybrid (SCSH) .......................... 70
  4.5.1 Latency and Throughput .................................... 70
  4.5.2 Interrogator Broadcasts ..................................... 71
  4.5.3 Contention ..................................................... 73
    4.5.3.1 IDO Operation .......................................... 74
    4.5.3.2 IP Operation ........................................... 74
    4.5.3.3 DP Operation .......................................... 75
  4.5.4 Capacitor Bank Requirements ................................ 75
  4.5.5 Eliminating $T_{TXRX}$ and $T_{RXTX}$ ....................... 77
  4.5.6 Piloted Trigger .............................................. 77
    4.5.6.1 Collisions .............................................. 78
    4.5.6.2 PHY Layer .............................................. 78
  4.5.7 Data Transfer ................................................ 79
  4.5.8 Summary ..................................................... 79
4.6 SCSH with Networked Interrogators (SCSH/NI) ................. 80
  4.6.1 PHY and MAC Layers in Brief ............................. 82
4.7 Architectural Summary ........................................... 84
  4.7.1 Implementation Review ..................................... 84
  4.7.1 Required Sensors ........................................... 85
  4.7.2 Range and Antenna Tuning .................................. 85
4.8 Conclusion .......................................................... 86
LIST OF TABLES

Table 2.1 OSI Seven-layer Reference Model .................................................. 18
Table 3.1 Human Tissues at 403 MHz [111] ......................................................... 36
Table 4.1 Frequency Bands Possibly Available for ISM Applications .................. 51
Table 4.2 Blind Tag Balance Sheet ................................................................. 58
Table 5.1 nRF905 Mode Switch Timing ........................................................... 89
Table 5.2 Minimum FS Packet ....................................................................... 90
Table 5.3 DP Packet .................................................................................. 96
Table 5.4 CMD Operations ........................................................................ 99
Table 5.5 nRF905 SYS Byte .................................................................... 102
Table 5.6 FS ID Reply ................................................................................ 102
Table 5.7 IP, DP and TDT Send Packet .......................................................... 103
Table 5.8 ACK / Send Packet .................................................................. 103
Table 5.9 Data Transfer Packet ................................................................. 103
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Hitachi RFID µ-chip 2003 (0.3 mm x 0.3 mm)</td>
<td>2</td>
</tr>
<tr>
<td>1.2</td>
<td>Basic Radio Blocks</td>
<td>3</td>
</tr>
<tr>
<td>1.3</td>
<td>Range Factors</td>
<td>13</td>
</tr>
<tr>
<td>1.4</td>
<td>Single Interrogator Use</td>
<td>14</td>
</tr>
<tr>
<td>1.5</td>
<td>Range Dependent Topologies</td>
<td>15</td>
</tr>
<tr>
<td>3.1</td>
<td>Tag Enclosure (Dimensions in mm)</td>
<td>29</td>
</tr>
<tr>
<td>3.2</td>
<td>Lossy Superstrate Effects [110]</td>
<td>35</td>
</tr>
<tr>
<td>3.3</td>
<td>Average permittivity and conductivity of wet otariidae skin. [109]</td>
<td>37</td>
</tr>
<tr>
<td>3.4</td>
<td>Power Duty Cycle</td>
<td>40</td>
</tr>
<tr>
<td>3.5</td>
<td>Shunt Capacitance Supply</td>
<td>43</td>
</tr>
<tr>
<td>3.6</td>
<td>Supercapacitor Package (Depth: 17 mm)</td>
<td>44</td>
</tr>
<tr>
<td>3.7</td>
<td>Switched Capacitor Bank</td>
<td>44</td>
</tr>
<tr>
<td>3.8</td>
<td>Capacitor Bank under Constant Load</td>
<td>45</td>
</tr>
<tr>
<td>4.1</td>
<td>FCC 15.231 and 15.232</td>
<td>52</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Star Network Topology</td>
<td>53</td>
</tr>
<tr>
<td>4.2.2</td>
<td>SCSH/NI Topology</td>
<td>54</td>
</tr>
<tr>
<td>4.3.1</td>
<td>Blind Transmit PHY</td>
<td>55</td>
</tr>
<tr>
<td>4.4.1</td>
<td>Trigger Beacon TDMA</td>
<td>59</td>
</tr>
<tr>
<td>4.4.2</td>
<td>Typical Detector Square-Law Response [126]</td>
<td>60</td>
</tr>
<tr>
<td>4.4.3</td>
<td>Passive Tag State Transitions</td>
<td>62</td>
</tr>
<tr>
<td>4.4.4</td>
<td>Detector PHY</td>
<td>63</td>
</tr>
<tr>
<td>4.4.5</td>
<td>Active Listen Duration</td>
<td>64</td>
</tr>
<tr>
<td>4.4.6</td>
<td>Detector Listening Mode</td>
<td>64</td>
</tr>
<tr>
<td>4.4.7</td>
<td>Hibernation Mode</td>
<td>65</td>
</tr>
<tr>
<td>4.4.8</td>
<td>Addressing 2ⁿ Batches</td>
<td>66</td>
</tr>
<tr>
<td>4.4.9</td>
<td>Cycled Detector State Transitions</td>
<td>68</td>
</tr>
<tr>
<td>4.5.1</td>
<td>Crude Attendance Pattern</td>
<td>70</td>
</tr>
<tr>
<td>4.5.2</td>
<td>Free Scan Mode</td>
<td>71</td>
</tr>
<tr>
<td>4.5.3</td>
<td>ID Report</td>
<td>72</td>
</tr>
<tr>
<td>4.5.4</td>
<td>Tag IDO Operation</td>
<td>74</td>
</tr>
<tr>
<td>4.5.5</td>
<td>Tag IP Operation</td>
<td>74</td>
</tr>
<tr>
<td>4.5.6</td>
<td>Demand Polling Operation</td>
<td>75</td>
</tr>
<tr>
<td>4.5.7</td>
<td>Worst Case Operation</td>
<td>76</td>
</tr>
<tr>
<td>4.5.8</td>
<td>Piloted Trigger</td>
<td>78</td>
</tr>
<tr>
<td>4.6.1</td>
<td>Island Topology with Overlapping Coverage</td>
<td>80</td>
</tr>
<tr>
<td>4.6.2</td>
<td>SCSH/NI Layering</td>
<td>81</td>
</tr>
<tr>
<td>4.6.3</td>
<td>NI: Round-Robin Polling and Tag Communications</td>
<td>82</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Managed Power Prototype</td>
<td>92</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Peripheral Payload</td>
<td>94</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Received Data Stream from Tag</td>
<td>95</td>
</tr>
<tr>
<td>5.3.2</td>
<td>FS Mode</td>
<td>97</td>
</tr>
<tr>
<td>5.3.5</td>
<td>Transfer to Tag</td>
<td>100</td>
</tr>
<tr>
<td>5.3.6</td>
<td>Transfer to Interrogator</td>
<td>101</td>
</tr>
</tbody>
</table>
Figure 6.1 Synchronous Tag Reporting ......................................................... 104
Figure 6.2 Microwave Power Detector ......................................................... 105
Figure 6.3 Power Detector With Low-Noise Amplifier .............................. 106
Figure 6.4 Microwave Pulse Generator ......................................................... 107
Figure 6.5 Complete Microwave Transceiver ............................................. 108
Figure 6.6 MSP430 Series Programmer ......................................................... 109
Figure 6.7 Sensor Payload Device ................................................................. 110
Figure 6.8 Interrogator Device .................................................................... 111
Figure 6.9 '1121A Protocol Platform ............................................................ 112
Figure 6.10 9.5 x 9.5 mm Loop Antenna ....................................................... 113
Figure 6.11 24 x 25 mm Loop Antenna ......................................................... 113
Figure 6.12 Shorted Half-Patch Inset Feed Antenna ..................................... 114
Figure 6.13 Current Monitoring ................................................................. 115
Figure 6.14 Interrogator / Tag Communication ........................................... 115
Figure 6.15 Communication Detail .............................................................. 116
Figure 6.16 Capacitor Bank Voltage Drop ...................................................... 117
Figure 6.17 Capacitor Bank Voltage With Unlimited Battery Draw ............... 117
Figure 6.18 Capacitor Bank Voltage With Limited Battery Draw .................. 118
Figure 6.19 Battery Terminal Voltage .......................................................... 119
Figure 6.20 Low Resolution Listen / Transmit Events ................................. 120
Figure 6.21 Regulator Instability ................................................................. 120
Figure 7.1 Tag Payload Arrangement .......................................................... 121
Figure 7.2 Battery Connection Detail .......................................................... 122
Figure 7.3 Cut-away View of Tag in Housing ............................................. 122
Figure 7.4 Short-Range Tag Utilizing IA4420 .............................................. 123
Figure 7.5 Long-Range Tag Layout ............................................................ 124
# LIST OF ACRONYMS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACK</td>
<td>Acknowledgement</td>
</tr>
<tr>
<td>ADC</td>
<td>Analog To Digital Converter</td>
</tr>
<tr>
<td>AM</td>
<td>Amplitude Modulation</td>
</tr>
<tr>
<td>ARPANET</td>
<td>Advanced Research Project Agency Network</td>
</tr>
<tr>
<td>ASK</td>
<td>Amplitude Shift Keying</td>
</tr>
<tr>
<td>ASP</td>
<td>Adaptive Share Polling</td>
</tr>
<tr>
<td>ATM</td>
<td>Asynchronous Transfer Mode</td>
</tr>
<tr>
<td>CCITT</td>
<td>Comité Consultatif International Téléphonique Et Télégraphique</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CITEL</td>
<td>Comisión Interamericana De Telecomunicaciones</td>
</tr>
<tr>
<td>CMD</td>
<td>Command</td>
</tr>
<tr>
<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
</tr>
<tr>
<td>COTS</td>
<td>Common Off-The-Shelf</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
</tr>
<tr>
<td>CSMA</td>
<td>Carrier Sense Multiple Access</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DP</td>
<td>Demand Polling</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct-Sequence Spread Spectrum</td>
</tr>
<tr>
<td>ERF</td>
<td>Event Repetition Frequency</td>
</tr>
<tr>
<td>ERI</td>
<td>Event Repetition Interval</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
</tr>
<tr>
<td>FBAR</td>
<td>Film Bulk Acoustic Resonators</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FDM</td>
<td>Frequency Division Multiplexing</td>
</tr>
<tr>
<td>FHSS</td>
<td>Frequency Hopping Spread Spectrum</td>
</tr>
<tr>
<td>FM</td>
<td>Frequency Modulation</td>
</tr>
<tr>
<td>FQPSK</td>
<td>Feher Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>FRAM</td>
<td>Ferroelectric Random Access Memory</td>
</tr>
<tr>
<td>FS</td>
<td>Free Scan</td>
</tr>
<tr>
<td>FSK</td>
<td>Frequency Shift Keying</td>
</tr>
<tr>
<td>GMSK</td>
<td>Gaussian Minimum Shift Keying</td>
</tr>
<tr>
<td>HIT</td>
<td>Hybrid Indirect Transmissions</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>ID</td>
<td>Identification</td>
</tr>
<tr>
<td>IDO</td>
<td>Identification Only</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute Of Electrical And Electronics Engineers</td>
</tr>
<tr>
<td>IP</td>
<td>Implicit Polling</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific And Medical</td>
</tr>
<tr>
<td>ISO</td>
<td>International Organization For Standardization</td>
</tr>
<tr>
<td>LAN</td>
<td>Large Area Network</td>
</tr>
<tr>
<td>LDO</td>
<td>Low Drop-Out</td>
</tr>
<tr>
<td>LEACH</td>
<td>Low-Energy Adaptive Clustering Hierarchy</td>
</tr>
<tr>
<td>LEACH-EM</td>
<td>LEACH For Event-Driven Data And Mobile Nodes</td>
</tr>
<tr>
<td>Li-VSO</td>
<td>Lithium Silver Vanadium Oxide</td>
</tr>
<tr>
<td>LNA</td>
<td>Low Noise Amplifier</td>
</tr>
<tr>
<td>LSB</td>
<td>Least Significant Bit</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MACA</td>
<td>Multiple Access With Collision Avoidance</td>
</tr>
<tr>
<td>MCU</td>
<td>Micro-Controller Unit</td>
</tr>
<tr>
<td>MEMS</td>
<td>Micro Electro-Mechanical Systems</td>
</tr>
<tr>
<td>MFSK</td>
<td>Minimum Frequency Shift Keying</td>
</tr>
<tr>
<td>MOSFET</td>
<td>Metal Oxide Semiconductor Field Effect Transistor</td>
</tr>
<tr>
<td>OAS</td>
<td>Organization Of American States</td>
</tr>
<tr>
<td>OOK</td>
<td>On-Off Keying</td>
</tr>
<tr>
<td>OQPSK</td>
<td>Orthogonal Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>OSIRM</td>
<td>Open Systems Interconnection Reference Model</td>
</tr>
<tr>
<td>PAMAS</td>
<td>Power Aware Multi-Access Protocol With Signaling For Ad Hoc Networks</td>
</tr>
<tr>
<td>PBP</td>
<td>Predictive Backoff Protocol</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PCM</td>
<td>Pulse Code Modulation</td>
</tr>
<tr>
<td>PEGASIS</td>
<td>Power Efficient Gathering In Sensor Information Systems</td>
</tr>
<tr>
<td>PEN</td>
<td>Prototype Embedded Network</td>
</tr>
<tr>
<td>PHY</td>
<td>Physical Layer</td>
</tr>
<tr>
<td>PIFA</td>
<td>Planar Inverted F-Antennas</td>
</tr>
<tr>
<td>PN</td>
<td>Pseudo-Random Noise</td>
</tr>
<tr>
<td>PPM</td>
<td>Pulse Position Modulation</td>
</tr>
<tr>
<td>PRMA</td>
<td>Packet Reservation Multiple Access</td>
</tr>
<tr>
<td>PSI</td>
<td>Pounds Per Square Inch</td>
</tr>
<tr>
<td>PSK</td>
<td>Phase Shift Keying</td>
</tr>
<tr>
<td>PWM</td>
<td>Pulse Width Modulation</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio Frequency Identification</td>
</tr>
<tr>
<td>RFID</td>
<td>Radio Frequency Identification</td>
</tr>
<tr>
<td>SAP</td>
<td>Service Access Point</td>
</tr>
<tr>
<td>SCADA</td>
<td>Supervisory Control And Data Acquisition</td>
</tr>
<tr>
<td>SCSH</td>
<td>Single Channel Sharing Hybrid</td>
</tr>
<tr>
<td>SCSH/NI</td>
<td>Single Channel Sharing Hybrid With Networked Interrogators</td>
</tr>
<tr>
<td>S-MAC</td>
<td>Sensor-MAC</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal To Noise Ratio</td>
</tr>
<tr>
<td>SONET</td>
<td>Synchronous Optical Network</td>
</tr>
<tr>
<td>SPI</td>
<td>Serial Peripheral Interconnect</td>
</tr>
<tr>
<td>TDM</td>
<td>Time Division Multiplexing</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TDT</td>
<td>Tag Data Transfer</td>
</tr>
<tr>
<td>THSS</td>
<td>Time-Hopping Spread Spectrum</td>
</tr>
<tr>
<td>TI</td>
<td>Texas Instruments</td>
</tr>
<tr>
<td>TRACE</td>
<td>Time Reservation Using Adaptive Control For Energy Efficiency</td>
</tr>
<tr>
<td>UART</td>
<td>Universal Asynchronous Receiver Transmitter</td>
</tr>
<tr>
<td>UHF</td>
<td>Ultra High Frequency</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless Sensor Networks</td>
</tr>
</tbody>
</table>
ACKNOWLEDGEMENT

I would like to acknowledge the support of the National Oceanographic and Atmospheric Administration, the North Pacific Universities Marine Mammal Research Consortium and the North Pacific Marine Science Foundation.

I thank Dr. Matthew Yedlin for his guidance and Dr. Shahriar Mirabbasi for his kind patience. Their efforts on my behalf are deeply appreciated. For her constant encouragement and valuable exchange of ideas, I thank Dr. Royann Petrell. Dr. William Dunford has provided practical system design advice, for which I am grateful.
CHAPTER 1 Introduction and General Background

Application-driven research has been the foundation of many advances in engineering science. The application that has driven this research is a new implantable radio frequency (RF) tag for identifying live Steller sea lion pups at haul-outs and rookeries. The dimensions of the housing proposed for the tag are 6 x 30 x 58 mm. While the use of RF tags in wildlife telemetry is not novel, long-term radio tracking of this (and other marine mammal) species is still problematic.

Three conflicting design goals move this project beyond the realm of relatively straightforward embedded RF system design into new territory. The device has to be small enough to be implanted under the skin of young pups; it must provide at least three years of operation, and the desired communications range is at least one kilometer. In the attempt to attain these goals, a team at the University of British Columbia investigated several interesting research areas including miniature antenna design, sensor networks, biomedical implants, biomechanics, embedded RF design, power management and protocol design.

William Shockley invented the junction transistor in 1948, and as this technology began to replace vacuum tubes, implanted electronics began appearing. In 1958 Åke Senning began implanting pacemakers designed by Rune Elmqvist into humans [1], heralding a wide range of implanted biomedical devices (e.g., cardioverter-defibrillators, cochlear implants, and spinal-chord stimulators). The earliest wildlife telemetry project was actually an implanted transmitter, used in 1959 by La Munyan et al [2] to monitor chipmunk heart rates.

Digital electronic circuits continue to shrink with lithographic improvements in integrated circuit processing and are becoming ever more capable. Remarkable advances in monolithic RF circuit design over the last ten years have seen cellular telephones with hundreds of components shrink to about one-fifth their previous size. They have vastly increased functionality (now including video cameras and even television tuners) and can operate longer from a smaller battery pack.
For most telemetry applications small size and low power consumption are attained at the expense of system longevity and range, particularly when the power supply is difficult to renew. Reducing size, cost, component count, weight and power consumption [3] has led to the development of many custom ICs targeted at telemetry applications [4-13]. A notable example is RFID (Radio Frequency Identification) technology. Some RFID tags are smaller than a pepper flake (Figure 1.1), have been implanted in animals and do not require a battery – but they have a very short range.

Figure 1.1 Hitachi RFID μ-chip 2003 (0.3 mm x 0.3 mm)

Our ID tags are intended for eventual use in several threatened species of marine mammal. Disturbing the animals is to be avoided, and once implanted the tags will remain untouched for the remainder of the animals' life. An RFID reader must be within centimeters of an implanted chip to read it, suggesting we cannot avoid the use of a battery by using RFID technology. Our ID implant must have its own power supply. Some biomedical implants use rechargeable batteries, but the inductive charger must also be close to the device and works best when placed against the skin. These considerations indicate that our ID implant requires a primary cell (i.e., non-rechargeable battery).

Figure 1.2 shows the basic functional blocks required of a wireless communications device. The electronics of the RF front-end and control circuitry can be made very small, using common off-the-shelf (COTS) products or custom circuit designs, but three items are not easily reduced in size: the reference oscillator, the battery and the antenna.
Typically, a frequency reference is generated by the acoustic resonance of a slab of material. Quartz is generally preferred, although ceramics are used when cost is the chief consideration. In both cases, reducing the size increases the resonant frequency. MEMS (micro electro-mechanical systems) technologies are beginning to utilize film bulk acoustic resonators (FBAR) for some microwave frequency devices, but this approach is generally application specific and (being intended for System-on-Chip designs such as cellular telephones) has not made its way into the COTS market as a discrete part.

The power available from a primary cell scales with the volume it occupies, so shrinking this component dramatically impacts the performance and functionality (i.e., the work) we can get from the device. Batteries have not seen the same scaling of size as electronics. Increasing volumetric energy density is obtained only at great expense with specialized fabrication processes.

The other component of a basic radio that does not scale well is the antenna. This limitation is explained in more detail in Section 3.2, but the situation is analogous to the acoustic resonance of a slab of quartz; the electrical resonance of a conductor is related to its size. Reducing the size of an antenna increases the resonant frequency. The problem here is that the electromagnetic waves of an antenna travel much faster than the acoustic waves of a quartz oscillator, so even microwave frequency antennas are of macroscopic dimensions.

When the dimensions of an antenna must be reduced, increasing the frequency of operation can maintain efficiency. However, for an implant a higher frequency of operation results in increased tissue losses, higher sensitivity to the detuning effects of changes in the surrounding tissues and increased propagation loss – all of which reduce
range. Reducing antenna dimensions without increasing the frequency of operation reduces efficiency.

Some wildlife telemetry implants use long antennas that are externally mounted and connected to the implant with conductors that penetrate the skin. These percutaneous antennas provide a path for infection and irritate the animal [14]. On the other hand, implanting the antenna reduces the range, due to tissue losses. Rather large tags (16 cm) implanted in the animal’s gut can accommodate electrically long antennas, but their performance is always worse than that of comparable external antennas [15]. Tissue effects can become a real problem when intraperitoneal implants are contraindicated, as antennas that are coplanar and adjacent to the skin must deal with the highly variable and lossy skin essentially becoming part of the antenna.

The high level goals of size, range and longevity all come at a cost: power. Reducing device size reduces available battery volume (i.e., power) and reduces antenna efficiency. In turn reduced antenna efficiency results in a shorter range. To maintain range, more power must be delivered to the antenna. Device longevity is directly proportional to its average power consumption; increasing longevity requires more power.

Power management is an important design concern. Little power is available due to the small volume available for a battery in the proposed tag. The objective of reducing the energy consumption of the tag is guided by the following principles:

a) Off-load complexity from the tag to the interrogator.
b) Off-load power requirements to the interrogator.
c) Minimize quiescent power consumption.
d) Preserve efficiency over device lifetime.
e) Reduce transmission durations through a minimalist signaling protocol.
f) Transmit only when reception is guaranteed.

These points are accomplished by ensuring that Physical layer (PHY) specifications and Medium Access Control (MAC) protocols work tightly together toward the same ends. Several alternatives have been developed and are covered in Chapter 4 Architecture.
Alternatives. Minimizing power consumption has become an important design goal of both integrated circuit and protocol developers; the efficient operation of RF transceivers and supporting circuitry is necessary for satisfying our design concerns.

Examination of existing telemetry networks and protocols, in particular wireless sensor networks and biomedical implants, assists in our system design. Both fields strive to increase device longevity and communications capabilities (e.g., data rates, range) while simultaneously reducing device dimensions.

Sensor network research addresses problems such as providing device longevity under tight energy constraints due to limited battery power, optimizing RF communication protocols to enhance system longevity and efficacy, and finding a balance between device functionality and longevity under severe resource constraints. Wireless sensor networks achieve long-range communication through multi-hop short-range signaling.

Biomedical implants further demonstrate our concerns about the interactions between tissue and implant, in addition to the sharp focus on power management required for systems where battery replacement is to be avoided. Implants that communicate via RF contend with tissues actually becoming part of the antenna. This difficulty is exacerbated for our tag as tissue layer characteristics will vary after implantation (when the mammal is a pup) until the end of the device’s lifetime, some three or more years later.

1.1 Telemetry Systems

Physical and data-link layer protocols of existing systems (wired or wireless) are often variations and refinements of standard approaches, adapted for the particular application. An examination of existing telemetry applications, computer network protocols, military standards, industrial systems and commercial applications, such as point of sale and telephony, provides a window into viable protocol standards. The physical layer protocols used by biomedical implants, wireless sensor networks and other systems that emphasize small size and low power consumption are of particular interest.
Generally speaking, electromagnetic signals (DC to daylight, wired or wireless) and pressure signals (acoustics, hydraulics and pneumatics) are used to carry telemetry signaling. An RF physical layer is most commonly used in telemetry applications, followed by infrared and acoustic physical layers. These are not mutually exclusive, being occasionally used together [16-18].

Some RF telemetry applications include: spacecraft telemetry [19], fetal monitoring [20, 21], civil infrastructure [22-24], biological experimentation [25], wildlife tracking [26, 27], sensor networks [28] and biomedical applications [29-37].

Infrared telemetry devices are used for short-range applications. They are not a source of radio frequency interference nor are they susceptible to such interference, which makes them popular for use in intensive care wards, newborn baby incubators and in biological and hospital laboratories. Infrared detectors have also been used in implants [38] but power requirements make them impractical as transmitters.

Acoustic telemetry is well suited to marine use as it is transmitted with low energy loss through seawater, whereas RF energy is rapidly absorbed. State-of-the-art underwater acoustic networks employ phase shift keying (PSK) in the physical layer, a MACA-derived (Multiple Access with Collision Avoidance) protocol for medium access control, and multi-hop routing techniques [39]. ATM-SONET protocols have been implemented in several undersea applications, including military towed arrays, seismic and geophysical arrays, and acoustic measurement ranges [40] alongside traditional proprietary communications systems.

Low power design is used in acoustic telemetry systems. This design approach includes the use of low voltage rails (1.8V logic), low speed clocks, high efficiency power supplies, the minimization of resource consumption and an emphasis on dedicated hardware rather than software for functionality. Often used for tracking marine animals [41] and human divers [42] acoustic LANs have attracted considerable research and development effort [43-47]. Effective ranges of 8 km in deep water and 4 km in shallow water [48, 49] have resulted in part from complex channel analysis [43, 50].
1.2 Wildlife Telemetry

1.2.1 Radio Techniques

Locating study animals in the field using small, simple radio frequency devices is known as radio tracking, while the transmission of information about animal behaviour, physiology and other metrics is known as radio telemetry. Telemetry devices are more complex as transponders must be sampled and data flow accommodated.

Conventional tracking systems identify individual tags using frequency division multiplexing (FDM) in combination with pulse signaling within each channel. The commonly used spectra in North America is 40.66 – 40.70 MHz, 162 – 174 MHz and 216 – 220 MHz, as these bands allow relatively high transmit powers.

A trained operator listening for a distinctive beep-beep-beep performs most tracking. Scanning receivers have largely supplanted manual tracking; scanning receivers monitor each channel in turn until a signal is detected, whereupon scanning is suspended so that the animal can be located.

More sophisticated systems that automatically scan, identify and log individual tags have been developed. Tags that shared a single channel by using different pulse rates exhibited varying longevities, driving the development of more sophisticated signaling in which pulse length encoding or orthogonal binary code representations are used. Orthogonal coding facilitates ID recovery in a noisy channel.

Significantly more complex is Zebranet, the work of Juang et al [51] who have used a sensor network to telemeter zebra herds. Supporting work by Liu and Martonosi is Impala [52], a middleware system for managing autonomic, parallel sensor systems. A wide range of system complexities exist for wildlife telemetry.

Radio signaling generally modulates one or more of the amplitude, phase or frequency of a carrier signal. Simple amplitude modulation (AM) as used for voice radio is rarely used in telemetry as “digital” approaches to modulation provide more robust, error-free transmissions. On-off keying (OOK) is often used [13, 53, 54]. This is a form of “digital” amplitude modulation that is also used in the implementation of various pulse
signaling schemes. These include pulse width modulation (PWM) [25], pulse code modulation (PCM) [42, 54, 55] and pulse position modulation (PPM) [42].

Frequency modulation (FM) is simply implemented with a single transistor [56], leading to some compact if not particularly robust transmitters, which are perfectly adequate for many wildlife tracking applications. Frequency shift keying (FSK) is popular with many monolithic transceivers [57] and is also used in some spread spectrum applications [58]. Phase shift keying (PSK) and its variations (QPSK, GMSK, OQPSK, FQPSK) have attractive spectral efficiency [55, 59-61] and are often implemented in monolithic designs. FM and PSK are the preferred modulation choices (ever try to listen to an AM station when driving through a tunnel?) for new designs using COTS products.

1.2.2 Attachment Techniques

Externally mounted telemetry devices are very popular and have proven effective for several species [62]. They are not completely unobtrusive, however, and may be subject to removal attempts, damage from the environment or other animals and shedding when adhesives fail. There is also some concern that any external device may affect animal behaviour or social interactions through physical interference, irritation or visibility. As the general purpose of telemetering wildlife is to ascertain natural behaviours and physiology, any telemetering method that significantly interferes with these observations is of questionable value. Recent studies have indicated that even breeding behaviours may be significantly impacted [63].

Collar-mounted devices are popular for terrestrial animals while adhesive-mounted or implanted devices are more popular for marine animals. Certainly collars are inappropriate for animals whose necks are not well-defined (e.g., snakes), whose heads are smaller than their necks (e.g., polar bears, seals) as well as for young animals expected to grow (e.g., our targets). External mounts of any sort are inappropriate when they might impede the animal (e.g., burrowers) or become an irritant (e.g., amphibians).

Internal implantation is appropriate and effective in many cases, including tracking fish [64] and some mammals [65]. Although the technique is initially invasive, correctly implanted they may be much less irritating than external tags. Implants intended
for small animals are very small and have limited range. Larger animals are better able to tolerate larger tags with correspondingly more efficient antennas; intra-abdominal implants work within a range of about 500 m [66]. External antennas are subject to damage and may lead to infection but are sometimes preferred to implanted antennas with an even shorter range [14]. Gastric implantation is adequate and easy for short-term studies [64] while intra-abdominal implantation is preferable for some longer-term studies [65].

1.3 Marine Mammal Application

Many populations of Steller sea lions (Eumetopias jubatus), northern fur seals (Callorhinus ursinus) and harbour seals (Phoca vitulina) have declined significantly in Alaska since the late 1970s. Radio frequency (RF) tags can help to explain these declining numbers by monitoring the movements and survivorship of young animals in the age classes at greatest risk.

Collar-mounted telemetry devices are inappropriate as these animals are expected to grow and have heads that are smaller than their necks. Devices externally attached to the animal with an adhesive provide only a limited lifespan, as they fall off when the animal molts or when grooming and other behaviours lead to mechanical fatigue. In addition, such attachments could affect social or foraging behaviours due to changes in the animals’ normally sleek, hydrodynamic profile [63].

An implantable device holds the promise of multi-year longevity, but comes with several difficulties. Field surgeries can be hazardous to animals. The administration of a general anesthetic (generally by rifle dart) can prove fatal if the animal flees into the water before the anesthetic takes effect. The haul-outs provide a septic environment, so that abdominal surgeries that breach the peritoneum carry a very high risk of infection and are too invasive to perform on young animals. The less invasive surgery required for sub-dermal insertion reduces the risk of infection and is accomplished more quickly, enhancing tag “roll-out” rates and therefore providing a statistically more robust study.

The position chosen for the tag is the animal’s head. When the animal is ashore, its environment may be cluttered with rocks and filled with other animals that may
obstruct or interfere with the tag communicating with an interrogator. When the animal lifts its head to look around, the antennas spatial diversity increases and may provide a window of opportunity for successful communications. Communication may also be possible when the animals are swimming as they often hold their head above water.

Changes in tissue layers and skeletal structure as the young animal matures also indicate the head as a preferred location. Little blubber growth occurs at the head, and skin thickness remains relatively constant as the animal matures. While a thick layer of low permittivity blubber surrounding the tag would benefit antenna performance, device migration in such a layer would prove disastrous. Packaging materials that anchor the device by promoting tissue adhesion (but avoiding encapsulation) is used to minimize device migration; this approach benefits from the minimal tissue fluctuations of the scalp. In addition, a slight concavity at the back of a Steller sea lion skull is exploited to position a slightly increased package thickness for the battery pack, which provides some additional mechanical stability.

Steller sea lions spend their time ashore at haul-outs or rookeries. These locations persist from year to year and provide a known congregation area where land- or sea-based interrogators may be positioned to collect telemetry data. As the interrogators’ size and power restrictions are considerably relaxed as compared to tags an opportunity exists to off-load device complexity and power requirements from the tags to the interrogators. This opportunity allows us to design protocols that ensure tags do not transmit without an interrogator present and that minimize wasted transmissions due to channel contention.

The fundamental functionality required by our system is to identify animals at the haul-out and to determine if they are alive or not. Determination of mortality will be accomplished with periodic monitoring of tag temperature. For reasons that should become clear in the rest of this paper, increasing tag utility by providing modest sensor data telemetry is attained at very little cost.

1.3.1 Longevity

For the intended application, it is essential that the tag functions for at least three years, during which time the host will mature from pup to a completely weaned juvenile. After
this time has elapsed the critical phase of the immature mortality study ends. Any operational lifetime of the tag beyond this point would not be of great use.

The tag's usefulness would increase dramatically if its functionality were expanded beyond identification and mortality indication only to include data-gathering from a sensor payload and telemetering of that data to an interrogator. A careful analysis of energy consumption and system performance is needed to assess the costs of including such capabilities. The flexibility of the SCSH and SCSHVI systems (Chapter 4) can provide this added utility.

A signaling protocol that minimizes the power required by the tag radio (for both transmission and reception) is fundamental to meeting even the base system requirements of identity and mortality. Chapter 4 presents several such protocols, with some allowing for the dynamic adjustment of tag behaviours to accommodate shifts in study emphasis.

The ideal maximum longevity of the device is dictated by the power source which, if primary cells are used, approaches that of the battery shelf-life. Chapter 3 discusses various renewable energy sources, some of which may find practical application as development progresses.

1.3.2 Range

Obtaining ranged communications from a tiny implant is a very thorny problem involving the interactions between power, size and skin. Let us begin this discussion with Harald Friis' famous formula that relates antenna gains, power levels, wavelength and distance:

\[ P_r = \frac{P_t G_r \lambda^2}{4\pi r^2 L} \]

Here \( P_r \) = Received power, \( P_t \) = Transmitted power, \( G_r \) = Receiver antenna gain, \( G_t \) = Transmitter antenna gain, \( L \) = System loss factor, \( \lambda \) = wavelength and \( r \) = distance separating transmitter and receiver antennas.

An interrogator needs to receive some minimum power \( P_r \) to hear a tag. If we boost the tag's transmitted power \( P_t \), the interrogator can be farther away. Operating from a very small battery the energy consumed per transmission must be small; the peak
transmission power may be increased without affecting energy consumption by reducing
the transmission duration. This simple solution quickly runs into some practical
difficulties. For instance, peak power levels are subject to regulation [67]. Also, COTS
integrated transceivers do not provide much flexibility with fixed data rates and low
power capabilities (~10 dBm). Even a roll-your-own transmitter capable of very short,
very powerful transmissions must deal with the antenna. A short pulse requires
bandwidth; the shorter the pulse the more bandwidth required. A narrow-band antenna
(as ours will be) effectively chops the pulse down, distorting it. Nonetheless, for any
given antenna we will strive to use the shortest, highest powered transmissions possible.

The system loss factor $L$ lumps together many sources of loss, especially if we
consider $P_i$ to be the power level at the transmitter (as we do here) and not the power
radiated from the antenna. For a small implant, antenna losses may severely impair
operation. When antennas become smaller than a quarter-wavelength of the RF carrier,
they become less efficient radiators. Shrunk down to a small fraction of a wavelength,
they might be radiating 0.1% or less of what they otherwise could. Retaining antenna
efficiency is a strong motivation for choosing a higher frequency of operation (i.e., a
shorter wavelength). Porrets’ view [68] is that hardware constraints and the tradeoff
between antenna efficiency and power consumption limits the frequency choice for tiny
transceivers to the UHF range (300 MHz – 3 GHz).

The skin poses a problem for high frequency operation. Antennas easily de-tune
(Section 3.2.1 Resonance and Superstrates) and the skin absorbs more power. We hope to
minimize de-tuning through careful antenna design and compensation circuitry, because
with too low a frequency a small antenna will perform very poorly.

On the other hand, $P_r$ also scales as $(\lambda/r)^2$, which means that doubling the RF
frequency results in one-quarter of the received power for a given distance. It is never
really as good as that (except in outer space, for instance) because signals might couple to
lossy materials, be absorbed, reflected, refracted and/or diffracted. Indoor propagation
typically scales as $1/r^4$ or worse, so to get the same range after doubling the frequency,
you might need 16 times more transmitted power! The $1/r^4$ scaling is also seen in outdoor
propagation when both transmitting and receiving antennas are at low elevation above the
ground, due to destructive interference from ground scattering.
So there is a dilemma. Lower frequency loses due to antenna inefficiency and higher frequency loses due to propagation losses. Our choices for the middle ground are limited by regulation as to what frequency bands are available for our use and the power levels permitted in those bands, barring special dispensation from the regulatory bodies. We will want to deliver as much power as we can to the antenna, so we must ensure we reduce power consumption elsewhere as much as possible.

Every one of the system blocks shown in Figure 1.3 affects the energy consumption of a tag. These factors are closely intertwined, as is reflected in this paper’s discussion of their interactions with each other and their subsequent effects on protocol design. Not shown is how electromagnetic radiation is used to accomplish communication, which involves frequency choice, modulation and information content. Note also that tissue participates as both part of the antenna and part of the channel. This is because it influences both the near-field characteristics of the antenna (i.e., it actually becomes part of the antenna) and the far-field behaviours (as it is a source of channel propagation loss in both directions).

![Range Factors](image)

Once the power source, electronics and antenna have been optimized for best operation at a given frequency, high tissue losses and channel losses may still result in an unsatisfactory range. Physical layer and MAC layer protocols would then have to be modified to try for higher peak power transmissions, or changes to the network topology may be required. I considered several combinations of hardware, protocols and system architectures.
Some sea lion haul-outs may be adequately covered by a single interrogator, as shown in Figure 1.4. A centrally located interrogator may be appropriate for a particular geography and not others, so alternatives include use by an off-shore buoy, handheld or field mounted devices, and surveys by seacraft or aircraft. The interrogator antenna design would differ according to the intended use, and for fixed installations should likely be tweaked to accommodate interrogator location, target population habitual location and intervening geography.

Some haul-outs along rugged coastlines or islands may prove difficult to cover with a single interrogator regardless of the tags' free-space communications range. Line-of-sight propagation is lost to rock formations, vegetation and other mammals. Tag freespace communications range may prove to be short range, and would necessitate the use of multiple interrogators or repeaters (Figure 1.5).
While a single interrogator would be used for ad-hoc marine or aerial field surveys, local geography and tag range may demand the use of multiple interrogators for fixed haul-out or similar installations. The power supply requirements as well as the complexity, size and expense of an interrogator vary considerably according to usage; the interrogator may be stand-alone or networked with others, and it may be used for ad-hoc surveys or for fixed installations requiring longevity.

1.3.3 Thesis Objective and Outline

The objective of this research was to develop various frameworks (i.e., communications architectures) and signaling methodologies (i.e., protocols) whereby the conflicting specifications for longevity, range, size and functional performance might be met. Further, adaptations of the idealized architectures and protocols necessary for prototype implementation using common off-the-shelf (COTS) parts were explored. The disparity between theoretical best-performance and compromised performance using less than ideal components were apprehended.

Chapter 2 is used to outline several approaches to Medium Access Control (MAC) for wireless communications systems. The Single Channel Sharing Hybrid (SCSH) MAC protocol proposed in this thesis combines several of these fundamental
approaches. The SCSH with Networked Interrogators (SCSH/NI) architecture also uses sensor network techniques.

Chapter 3 covers the Physical layer (PHY) requirements of very small wireless devices in general and the additional complications presented by implantation in particular. Application-specific data transfer requirements, antenna concerns and power management issues form the core of this section.

Chapter 4 is used to examine system architecture alternatives and the compromises to be made in selecting an architecture. An attempt is made to blend high-level assessments with low-level considerations. The chief architectures outlined are Blind Transmit tags, Pulse Triggered systems, the SCSH approach and its extension via Networked Interrogators, SCSH/NI.
CHAPTER 2 Medium Access Control Layer

Discussions of wireless communications inevitably lead to a deluge of acronyms. Several of the acronyms used here represent a particular fundamental approach to conducting wireless communications. As wireless communication has many aspects, a common framework is required to maintain intelligibility for all the many variations out there. Hardware, radiation and information are all that are required for wireless communications; combining these fundamental elements leads immediately to complexity.

This chapter is concerned with the use of the electromagnetic spectrum. Devices using the same portion of the electromagnetic spectrum to communicate must have a framework for controlling access to the signaling medium. Section 2.1 presents a common communications framework to provide context for this and subsequent discussions, while the rest of the chapter outlines some fundamental approaches to sharing the medium.

2.1 Open Systems Interconnection Reference Model

A conventional framework for the development of protocols is the seven-layer Open Systems Interconnection Reference Model (OSIRM), produced by the ISO (International Organization for Standardization) in 1979 and recognized by the CCITT (Comité Consultatif International Téléphonique et Télégraphique). The initial experimental computer networks, such as ARPANET, were intended to be heterogeneous, but each manufacturer interconnected their equipment as they saw fit, creating many different network architectures. The OSIRM was promoted as a standard, allowing diverse manufacturers of informatic networks to design for interoperability with all other systems obeying the same “open” standard. The functional compartmentalization provided by the model is of benefit in analyzing protocol alternatives and understanding existing ones.
Most practical communications protocol implementations do not fit the model perfectly, having null layers and sub-layers (Ethernet) or transgressing prescribed layer interactions (e.g., Telnet (RFC 854) protocol, Internet FTP (RFC 959), DNS). The value of the OSI Reference Model is that it provides a general framework and as such is heavily used by industry and bodies such as the IEEE standards committees. The IEEE Ethernet data link layer consists of two sublayers and may perform transport layer services:

- **Media Access Control (MAC) Sublayer (802.3)** – Responsible for how data is transported over the physical wire. Defines physical addressing, network topology, line discipline, error notification, orderly frame delivery and optional flow control. Communicates down to physical layer.

- **Logical Link Control (LLC) Sublayer (802.2)** – Logically identifies different protocol types using a type code or service access point (SAP) identifier and encapsulates them. Sometimes performs transport layer services.

Wireless systems perform a similar sub-layering, differentiated from wired systems by stipulating “Medium” rather than “Media” for the MAC sublayer.

The Physical (PHY) layer “...provides mechanical, electrical, functional, and procedural characteristics to establish, maintain, and release physical connections (e.g., data circuits) between data link entities”[69]. Services provided by this layer include
physical connections, circuit identification, bit sequencing and the provision of fault notification to data-link entities. Essentially it is concerned with the low-level functioning of hardware.

Power consumption, RF modulation and antenna design are physical layer concerns that must be addressed to meet the design goals of communications range and device longevity.

The Data Link layer is concerned with moving data through the channel in an error-free manner, establishing connections, service availability, latency and throughput. The gritty details of medium access control (MAC) can make or break low-power systems that share a medium - as is the case for our application. Efficient and effective use of the channel is essential to low-power telemetry, particularly with many transponders. To reduce power consumption, a MAC protocol specific to the application is often developed [31, 46, 70-80]. The system architecture options presented here have very low offered traffic in a single-hop, star topology - excepting the topological extension of networked interrogators presented in section 4.6 SCSH/NI.

The Network layer provides message routing, synchronization, negotiation and coordination. The Transport layer is concerned with machine to machine transfer rather than process to process; it splits data into smaller packets for transport. These two layers are of concern for the SCSH/NI architecture. Network protocols there should be largely based on the work done for wireless sensor networks (WSN).

The sparse data transfer requirements and limited connectivity of this application are well encapsulated by two protocol layers, provided the information transfer requirements of the application layer are kept in mind. The goal of our analysis is to devise an energy-frugal hardware behaviour that supports aggressively optimized signaling in a power-aware network. Implant design must focus on reducing the energy consumption of the data flow layers of the OSIRM (Physical, Data Link, Network and Transport). I took a similarly pragmatic approach in using the OSIRM as a semi-flexible tool rather than coercing system functionality to match the model.
2.2 Multiplexed Collision Avoidance

A fundamental task of the medium access control (MAC) protocol is to avoid collisions. Multiplexing of a channel shared by several devices is performed by the MAC protocol, which in some cases emphasizes throughput and minimal latency over collision avoidance. For our implant development, collision avoidance is emphasized as throughput is minimal and latency is not an issue.

Collision avoidance is of concern for systems with multiple users. Fundamental approaches to sharing the system's spectral bandwidth as a single channel include "first come, first served" contention-based protocols such as IEEE 802.11 and ALOHA, and "take your turn" protocols based on time division multiple access (TDMA) techniques. When more than one channel is available, approaches such as frequency division multiple access (FDMA) and frequency hopping spread spectrum (FHSS) may be used to accommodate multiple users. Yet others that treat the entire band as a single channel allow several uncorrelated signals to occupy the channel simultaneously through use of spread spectrum techniques such as code division multiple access (CDMA) and other direct sequence spread spectrum techniques. Hybrid approaches may mix-and-match these fundamental ideas.

Time Division Multiplexing (TDM) or equivalently Time Division Multiple Access (TDMA) assigns timeslots for devices to access the channel. Frequency Division Multiplexing (FDM) partitions the available channel spectrum into multiple smaller channels, whereby multiple devices may use the transmission channel simultaneously. In the context of a telemetry system with multiple sensors, TDMA scheduling is popular due to its well known energy efficiency. It is used in infrared systems [81], acoustic systems [82] and RF (radio frequency) systems [78, 83]. A form of FDM is sometimes implemented when a sub-channel is used for pilot information or when interrogator and sensor transmit and receive on complimentary frequency bands [76, 84].

Spread Spectrum techniques modulate the message over the entire channel so that simultaneous messages do not interfere with each other. Stojanovic et al explore the use of Spread Spectrum techniques in acoustic systems [58], considering direct-sequence spread spectrum (DSSS) systems that employ digital phase modulation with coding and FHSS systems that employ coded minimum frequency shift keying (MFSK) modulation.
In medical applications such as patient monitoring, FHSS is the more robust spread spectrum technique as it provides seven times more processing gain than DSSS [85]. We shall look at examples of these approaches and their use in implantable telemetry in the following sections.

2.2.1 Contention-based

Contention-based MAC protocols use the channel in an on-demand fashion. Low throughput systems (i.e., when the usage of the channel is much less than the capacity of the channel) may overcome collisions through redundant transmissions, while busier channels implement some form of timing control. For example, sensing the channel for activity before transmission or introducing a time-slotting approach may be used. Following the collision of a transmitted packet, several “back-off” or delaying schemes are available which decrease the likelihood of subsequent retransmissions colliding.

2.2.1.1 ALOHA

The first wireless data network to employ a random channel access protocol was the ALOHA system, which provided a link between the University of Hawaii and outlying islands. This network uses a star topology, with the university node receiving all transmissions from the remote sites on one RF channel and replying on a second RF broadcast channel. Remote sites transmitted message packets of 704 bits at 24 kBaud without regard to if another site was currently using the same channel. When a message collision occurred, the senders simply re-transmitted after a random delay (or backoff time). IEEE 802.11 uses a Predictive Backoff Protocol (PBP) as a refinement of this backoff delay.

For a given offered traffic rate, ALOHA maximum throughput is $1/(2e) \approx 0.184$ [86]. This apparent channel inefficiency has been improved by protocols such as slotted ALOHA, allowing for higher throughput. However, for seldom used channels with poor signal-to-noise ratios (SNR), throughput is not always the best figure of merit to use. Abramson notes that
"... we see that the channel efficiency of an ALOHA channel approaches one for the important case of small values of throughput and small values of the signal-to-noise power ratio. In other words, under these conditions it is not possible to find a multiple access protocol which has a higher capacity for a given value of average power and a given bandwidth." [86]

An ID tag has extremely small throughput requirements, and actively minimizing the SNR conserves battery life. A variant of the ALOHA approach is described in section 4.5.6 Pilot Trigger, with the addition of the master node transmitting a pilot signal and a deterministic backoff algorithm.

2.2.1.2 SCADA

In industrial applications, wireless SCADA (Supervisory Control and Data Acquisition) networks endpoints, which have no local power available, tend to use transmit-only sensors. The required sample rate of the endpoint sensor drives technology options [87]. The requirement for one-way or two-way communications must be identified: one way costs less as transmitters are about one third the complexity of a transceiver and spread spectrum transceivers use more power than transmitters. To mitigate collisions the typical "poll/response" approach is avoided for transmit-only endpoints through redundant transmissions. Axonn SCADA systems with 28-second transmit intervals can accommodate 100 sensors during a 200-second supervisor interval. A 1.4 Ah battery will last for more than 2 years at this rate (100 mW, 7ms transmissions, 5μA sensor current).

This approach is similar to that used in 4.3 Blind Transmit and has been used in wildlife telemetry for many years. Despite a low reporting rate to attain three-year longevity, this approach makes it easier to implement high-power designs as a receiver does not share the antenna. Using a power amplifier with a COTS transceiver requires the use of an antenna switch, which comes at the cost of real estate, power loss and expense.
2.2.1.3 Carrier Sense Multiple Access (CSMA)

This rather large family of protocols improves the throughput of ALOHA access by “sniffing” the channel for traffic before transmission occurs. This is not foolproof though, and if a collision occurs, retransmission is typically delayed by a random backoff period.

However, a central node might be able to “see” two neighbour nodes that cannot see each other. A neighbour node might begin transmitting to the central node while the other neighbour is in communication with the central node. One approach to solving this “hidden terminal” problem is for a node that is communicating with a neighbouring node to broadcast a “busy tone” on a second channel. This approach increases system complexity and requires more bandwidth and power.

An ID tag can not afford to transmit a busy tone, but the interrogator, which is the central node of the 4.5 Single Channel Sharing Hybrid (SCSH) architecture and in particular the 4.5.6 Pilot Trigger, can pay the price of supplying a call/do not call tone – much to the benefit of tag power requirements. These architectures require both tag and interrogator to be capable of sensing the carrier. This sensing forms the basis of both collision avoidance and transmission triggering for these approaches.

2.2.2 FDMA

Frequency division multiple access avoids collisions by assigning devices different frequency channels to transmit in. This strategy is often combined with a TDMA approach where each channel is further subdivided into assigned time slots.

FDMA will allow several SCSH systems to coexist spatially as each system occupies a single channel only. Both 4.5.6 Pilot Trigger and 4.6 SCSH/NI architectures use two or more channels. Although this is evidence of frequency diversity, only SCSH/NI uses more than one channel for multiplexed communications.

2.2.3 Spread Spectrum

Spread spectrum techniques allow simultaneous channel access by manipulating a data signal such that the bandwidth occupied by the transmitted signal is much larger than that required by the data signal. The ratio of the spread spectrum signal bandwidth to the
Information bandwidth is a figure of merit known as processing gain. Spread spectrum systems often strive to increase processing gain (typ. 20 – 254) to increase the number of users that can simultaneously access the channel and to mitigate multi-path effects.

Several different approaches to spread spectrum modulation exist, including Direct-Sequence spread spectrum (DSSS), Frequency-Hopping spread spectrum (FHSS), Code Division Multiple Access (CDMA) and Time-Hopping spread spectrum (THSS).

DSSS multiplies (or “chips”) a data signal with a pseudo-random noise (PN) signal to spread it. To avoid self-jamming when multiple users transmit, the users must be perfectly synchronized so that chip boundaries are aligned. Near-far fading is a problem, but high data rates are possible. DSSS is implemented in 802.11b and provides a maximum over-the-air data rate of 11 Mb/sec.

FHSS spreads transmission bandwidth by hopping from frequency to frequency according to a pseudo-random sequence. Data rates are less than DSSS as less spectrum is available in each hopping channel. FHSS is generally regarded as having better interference immunity than DSSS.

CDMA uses orthogonal chipping codes unique to each user to spread transmission bandwidth. Overlapping transmissions do not collide, as they are recoverable through correlation with the unique codes. The Berkeley Wireless Research Center proposed using CDMA for their PicoRadio program, for which they also proposed developing a low-power “wake-up radio”. The wake-up radio shares the same architecture as the Pulse Trigger (Section 4.4), being an RF amplifier, filter and detector.

THSS transmits a chirp pulse either in a pseudo-random position relative to the input bit period or with a pseudo-random pulse duration. This technique adds another layer of matched filtering to the signal processing requirements; THSS systems are rarely implemented commercially.

Use of relatively high power transmissions (1 W) in the 915 MHz, 2.4 GHz and 5.8 GHz ISM bands is limited to DSSS and FHSS systems. Free-space systems might attain a nearly 2-km range with these power levels. The immediate difficulty with implementing DSSS for an implanted tag is the bandwidth requirement; the implanted antenna is unlikely to provide sufficient bandwidth for typical DSSS signaling. FHSS may be implemented in an implanted tag. In this approach, the carrier frequency changes
according to a pseudo-random noise (PN) sequence. A particularly agile and accurate antenna-tuning mechanism would be required to accommodate multi-channel hopping. However, regulations require a minimum of 50 synchronized channel hops by both transmitter and receiver. Synchronization issues and system complexity make FHSS a questionable approach for tag ID transmissions but could be used for data telemetry.

DSSS and FHSS are of particular interest for the SCSH/NI architecture. The available power level and multi-path benefits make spread spectrum an attractive interrogator modulation approach.

2.2.4 TDMA

A very popular MAC approach, time division multiplexing finds many applications and many variations. Wireless sensor networks have benefited from the development of many such approaches [88] and is covered in more depth in Section 2.3 Sensor Networks.

The Implicit Polling Operation of the SCSH MAC protocol is a reply phase that uses the TDMA approach. Equivalently, it is a retransmission back-off mechanism with explicitly pre-assigned back-off delays. Yet another way to look at it is as a sequential polling with the system poll synchronization being inferred from the time of collision rather than from an explicit poll signal.

2.2.4.1 Polling

A master node regularly polls individual nodes, providing them with uncontested time slots for communication. This approach is highly deterministic as the master node drives all network traffic and can provide different service levels to specific nodes as needed. Network topology is again a star network, requiring nodes to be within range of a master in order to be polled and to respond to that poll.

Polling requires node receivers to operate long enough to detect a poll in the systems poll-response traffic pattern. The SCSH MAC protocol uses addressed polling when in Demand Polling operation (Section 4.5.3.3) and a broadcast poll/random-access hybrid during normal operation.

Bluetooth networks use polling channel access. ASP (Adaptive Share Polling for Bluetooth) uses a central controller to poll its slaves during certain time slots to which all
Piconet members are synchronized. It is concerned mainly with appropriate scheduling of polling in order to dynamically respond to the data traffic requirements of present nodes. Various power reduction modes for nodes participating in the network are available, including fixed period sleeps (HOLD mode), specific time slot sleeps (SNIFF) and extended sleeps during which the node may be removed from the network (PARK). SCSH uses similar suspensions to accommodate demand polling, data reporting and hibernation mode.

2.3 Sensor Networks

These self-organizing networks are generally comprised of many short-range transponders that transfer data through the network via their linked neighbours. Frequently a single transponder is elected to transmit accumulated network data to an interrogator in order to spread the energy cost of this expensive operation.

Potential applications for sensor networks exist in biology, physics, medicine and the military. A major challenge is to maximize network life under the constraint of an extremely limited power supply. This constraint is particularly difficult to ameliorate when the sensors are bio-implants or otherwise inaccessible.

Sensor networks are characterized by peer-to-peer communication among the sensors, a characteristic of mobile wireless networks [89] used for habitat monitoring [87]. Energy-aware protocols such as PAMAS and S-MAC [90] emphasize energy conservation and self-configuration over per-node fairness and latency.

Communication in sensor networks consumes the lion’s share of power [77] with the assumption that transmission is the most expensive operation [91]. Routing protocols increase efficiency through power management systems, data fusion, chaining and clustering. Chaining and clustering minimize transmission costs while data fusion reduces packet size. Examples of chaining protocols include PEGASIS (Power Efficient Gathering in Sensor Information Systems) [92] and the chain hierarchy protocol [93]. An example of clustering architecture is LEACH [77]. These approaches are used when a single head node of a given cluster fuses data collected from nodes within the cluster for a single transmission to the central data collector.
MAC protocols for sending data from sensor nodes directly to the central data collector include LEACH-EM (LEACH for Event-Driven Data and Mobile Nodes), TRACE (Time Reservation using Adaptive Control for Energy Efficiency), PBP (Predictive Backoff Protocol for IEEE 802.11), HIT (Hybrid Indirect Transmissions) and ASP (Adaptive Share Polling for Bluetooth). These local data delivery protocols attempt to make efficient use of the limited sensor energy budget while handling network dynamics. All make use of TDMA (Time Division Multiple Access) scheduling due to its well-known energy efficiency, but there are several approaches to implementation. Schemes include a-priori scheduling, distributed scheduling, reservation-based scheduling and controller learned scheduling.

LEACH cyclically assigns an active head node that assigns reporting time-slots to the remaining nodes, which otherwise sleep. This sharing of the head node role is highly efficient for static networks that always have data to send. LEACH-EM [77] extends this approach to mobile networks, where nodes avoid wasteful transmissions by performing a “handshake” with the cluster-head and suspending transmission when the node is out of range. The node still listens for a handshake transmission from the cluster-head at the expected time to determine when it is again within range.

TRACE transmits a beacon message to announce a new frame. Sensors with data to send that do not have a reserved timeslot, randomly choose a slot to reply in. Once collisions are resolved, the timeslot is reserved for that node for as long as it has data to transmit, a technique borrowed from the Packet Reservation Multiple Access (PRMA) protocol [94]. A refinement to resolving timeslot contention is the Wireless BioDevice Network.

PBP is based on the IEEE 802.11 two-way handshaking (DATA-ACK) protocol. TDMA scheduling is accomplished not by a central node but in a distributed fashion where each node picks a backoff time (i.e., slot) before transmission and includes this information in its data transmission. It is less energy efficient; as ACK messages are required for every DATA message, sensors must always be awake, and there is no guarantee that collisions will not occur.

The SCSH/NI architecture is conceived as a layered wireless sensor network. A fixed network of interrogators collects tag data, periodically pooling that data and
reporting over a satellite or mobile link. Uplink duties must be shared, inter-interrogator synchronization is required (to avoid confusing the tags) and the gathered data must be pooled.

2.4 Conclusion

Contention-based access (or random-access) is very efficient for a sparsely populated, low data rate network such as we will implement. A triggering signal from an interrogator can serve a dual purpose in also providing synchronization, which allows synchronous access methods based on the TDMA archetype. SCSH uses a triggered random access with a TDMA back-off algorithm and provides polling access as well.

SCSH/NI encompasses the hybrid protocols of SCSH as used for tag communications and uses spread spectrum modulation with sensor network communications. These various MAC protocol approaches are very useful tools in crafting application-specific variations.
CHAPTER 3 Physical Layer

A consequence of using a sub-dermal tag is that the device must be very low profile. The device's mechanical and chemical integrity must be preserved over the animal's entire lifetime (~ 30 years) and survive the pressures of repeated dives to depths of up to 300 metres with pressures exceeding 455 PSI (aka 32.12 kg/m², 3.14 MPa or 31 atm). An enclosure was designed within the research group. It is intended to provide mechanical strength, prevent chemical leaching, promote tissue adhesion (to prevent migration) and minimize scar tissue.

![Figure 3.1 Tag Enclosure (Dimensions in mm)](image)

The enclosure is made of alumina with dimensions as shown in Figure 3.1. The small volume available for the tag (3.96 cm³) tightly constrains energy capacity, antenna geometry and electronic device suitability. With this as a starting point, this thesis will attempt to reconcile longevity and range goals with the stringent constraints on battery and antenna size.
3.1 Physical Layer Goals

The two biggest concerns for the Physical layer (PHY) implementation of an implant are the battery and the antenna (see Chapter 1). It is of equal importance that the electronics design makes effective use the battery and antenna. This design is closely tied to the particular approach taken; these PHY layer concerns are addressed on a case-by-case basis in Chapter 4 Architecture Alternatives. This chapter will discuss the fundamental application information transfer requirements, antenna design issues and power management issues.

3.1.2 Information Transfer Requirements

With a high-level view of what we want the system to accomplish, we can take advantage of two critical features in specifying what the PHY layer of a tag should accomplish: location and information rate.

3.1.2.1 Locale

First, we are gathering data at a particular location. A tag needs to transmit only when it is present at a haul-out that is being monitored. Therefore, the tag PHY layer can conserve energy if it can discern:

a) when the animal is at sea or ashore
b) when ashore, if the location is monitored

Several data delivery models for MAC layers exist, including continuous [25], event-driven [77], interrogator initiated [95], time-triggered [96, 97] and hybrid [91]. If we are able to implement an observer-initiated data delivery model (i.e., an interrogator prompts the tag for a transmission) the tag will waste no energy on transmissions that do not have an audience. Further, we might position interrogators such that a tag entering the locale will be identified.
3.1.2.2 Information Rate

Second, the information conveyed by a tag transmission is minimal, being essentially a binary state. The interrogator may summarize the information as Tag N is here, or Tag N is not here. Assume a tag is required to report to an interrogator at most once every 15 minutes. Over the course of an hour, information throughput is essentially four bits. This allows considerable latitude to the system's PHY and MAC layers (i.e., interrogator and tag working together) as to how to embed the tag ID number N in that single bit of information transfer. Some MAC approaches include:

a) Use tag transmission timing to indicate N. This is used in 4.4 Pulse Triggering and IP (Implicit Polling) operations of the SCSH MAC (Section 4.5.3.2) and the SCSH/NI systems (Section 4.6).

b) Explicitly poll for the tags by ID. This approach is used in the scalable version of Pulse Triggering and the DP (Demand Polling) operations of the SCSH and SCSH/NI systems.

The implications for tag PHY layer implementation are that should either a) or b) above be implemented, any tag transmission detectable by the interrogator will accomplish the required information transfer. This implies that a tag transmission of very high power and very short duration might be used to increase range while maintaining very low average power consumption. While all approaches presented here attempt to minimize the duration of a transmission, a transmission along the lines of a very powerful single carrier cycle can only be attempted in the instances mentioned in a) and b) above.

Failing a) or b), the tag transmission must contain unique identification information. The modulation of that information is dictated by the capabilities of the COTS products chosen for a specific implementation, or it may be determined by the designer should a custom-made integrated circuit be implemented.

The application also needs to collect mortality information. The tag must periodically monitor ambient temperature, which is used to deduce animal mortality. The implied mortality state of any reporting tag is "alive." Should the animal die near an interrogator, that fact is the last datum communicated for the remainder of the device's
battery life. This is a corner case where battery life just does not matter any more and so will not have much impact on physical layer design beyond the sensing requirement.

3.1.2.3 Additional Information Transfer

Device utility would increase significantly by increasing information transfer. Control information from the interrogator could affect the behaviour of a tag capable of half-duplex communications, allowing for reallocation of the tags' power budget based on observed behaviours and study focus. Tag data transfer capability allows for sensor data telemetry.

This additional information transfer can be accomplished without impacting device longevity. Average tag power consumption can be kept constant following an expensive data transfer by (for example):

- Extending hibernation following data transfer
- Temporary reductions in listening frequency
- Block hibernations (e.g., Hibernate all of February)

This functionality might be particularly useful should long-term behaviours present an opportunity for increasing tag utility. For example, the animal spends the summer months in a region without monitored haul-outs, or the animal always remains at the haul-out for at least six hours following a foraging trip. Once such patterns have been discovered they can be exploited to increase tag utility and/or longevity.
3.2 Antennas

For implanted telemetry devices, tissue losses may be large [98, 99]. The risk of infection and physical damage in using an external antenna with transcutaneous leads [35, 100, 101] makes this approach inappropriate for long-term implantation. The effects of tissue on an implanted antenna cannot be ignored [102-107] as the expected range of low power transmissions is generally less than 15 metres [84, 108]. It is essential to maximize antenna performance.

An antenna converts the movement of charge into electromagnetic radiation and vice-versa, with radiation being a phenomenon associated with the acceleration of electric charge. An antenna performs best when it is driven at resonant frequency and requires good matching to the driving (and driven) circuitry to operate efficiently.

3.2.1 Resonance and Superstrates

Electromagnetic fields propagate through a medium with a speed that depends on the medium’s intrinsic properties; in free-space these properties are the permittivity of free space $\varepsilon_0$ and the permeability of free space $\mu_0$. Free-space speed $v$ is the speed of light:

$$v = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \approx 2.99792 \times 10^8 \text{ m/s} = c$$

An increase in the effective permittivity of the medium ($\varepsilon_r > 1$) serves to “slow down” propagation. An antenna is constructed so that the largest conductor dimension $L$ is typically related to the wavelength $\lambda$ of the resonant frequency $f_r$ as $L = \lambda/2$ or $L = \lambda/4$. Relating this to the speed of propagation $v$:

$$2L = \lambda = \frac{v}{f_r} = \frac{1}{f_r \sqrt{\varepsilon_r \varepsilon_0 \mu_0}}$$

When $v$ decreases, $f_r$ decreases for the antenna; it resonates at a lower frequency. Anticipating this, antenna designers may surround an antenna with high permittivity.
material, thereby reducing the size of the antenna required to resonate at a particular frequency. This approach is often used for planar antennas printed on a substrate, such as a patch antenna.

Shrinking a patch for use in an implant might at first appear attractive. The height restrictions and lateral dimensions drive the design to high frequency operation, however. Using very high permittivity substrates reduces the required patch dimensions by $\approx \frac{1}{\sqrt{\varepsilon_r}}$, but also decreases radiation efficiency and bandwidth. Nevertheless, this compromise might otherwise be acceptable but for the additional effects the skin layer has on antenna behaviour. The tissue acts as a very high ($\varepsilon_r \approx 30 - 50$) permittivity superstrate that is also very lossy ($\sigma_e \approx 0.68$) [109].

A patch designed for 2.4 GHz operation on a substrate of $\varepsilon_r = 9$ has a half-wave dimension of $\approx 20.8$ mm. This would fit available tag volume, provided the ground plane was short-changed somewhat. With sea lion skin thickness of 3 – 5 mm, the normalized superstrate thickness for Figure 3.2 is < 0.1. This is good news for the radiation efficiency (left chart) but bad news for resonance shifts (right chart). The relative thinness of the superstrate makes antenna resonance extremely sensitive to changes in superstrate thickness and in superstrate loss.

The loss inherent in sea lion skin is strongly influenced by diet, as well as blood perfusion and the brine content of their fur. Worse, these concerns are highly variable. De-tuning of patch antennas would be a severe problem.
Anything that gets near an antenna can affect its operation. An antenna tuned for one set of environmental conditions may not perform at all under a different set of environmental conditions. The resonance shifts of a patch antenna are accompanied by an impedance shift. The feed-point for the patch must be precisely located to attain the desired input impedance; a resonance shift provides a relative feed-point shift as well. Tuning a patch would involve correcting for both changes, which makes this difficult to implement.

As the animal tissues are in close proximity to the antenna they strongly influence the near-field and should even be considered part of the antenna. The antennas lack of isolation from its surroundings means that a strong interaction exists. Currents interacting with near-field elements may be trapped and lost or may disturb the antennas' input impedance, resulting in decreased antenna efficiency.

3.2.2 Tissue Issues
Radio frequency communications occurring on the rocky islands and shorelines of the ocean face major challenges in providing reliable operation. The problems of multipath,
shadowing and absorption when operating close to ground level are exacerbated by the use of an inefficient antenna implanted in a lossy medium.

After a tag is implanted under a young animal's skin, the characteristics of the tissues that surround the tag antenna are likely to exhibit significant variations over both the long-term and short-term. The impact of these variations must be mitigated or accommodated through antenna design. Variations occur over the three- (or more) year lifespan of the device due to animal maturation and to seasonal climatic change, fur growth and molting and feeding patterns.

Tissue variations include changes in skin thickness and fat layers and variations in the complex permittivity of those layers according to animal physiology. The seasonal growth and molting of fur presents the periodic occurrence of an additional layer, which may also retain brine or organic matter.

Short-term (i.e., hours or minutes) variation may also occur due to the effects of blood perfusion in the tissue. Blood is a source of loss and affects the tissue's effective permittivity. The cold water and high pressures experienced during foraging dives force blood from the scalp capillaries; the recovery time once the animal is hauled-out is not known, nor are the potential effects of ambient temperature changes. Brine retention by a fur layer might also inhibit communications until the brine drains away, evaporates or is otherwise removed.

The effective permittivity $\varepsilon_r$ and conductivity $\sigma_e$ at 403.5 MHz of various human tissues are given in Table 3.1 and are from Gabriel [111]. Measurements of the characteristics of wet Steller sea lion skin over a range of frequencies (Olawale et. al. [109]) are shown in Figure 3.3.

<table>
<thead>
<tr>
<th>Tissue</th>
<th>$\varepsilon_r$</th>
<th>$\sigma_e$ (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muscle</td>
<td>57.1</td>
<td>0.797</td>
</tr>
<tr>
<td>Fat (non infiltrated)</td>
<td>5.6</td>
<td>0.041</td>
</tr>
<tr>
<td>Dry Skin</td>
<td>46.7</td>
<td>0.690</td>
</tr>
<tr>
<td>Wet Skin</td>
<td>49.8</td>
<td>0.670</td>
</tr>
</tbody>
</table>

Table 3.1 Human Tissues at 403 MHz [111]
Figure 3.3 Average permittivity and conductivity of wet otariidae skin. [109]

In Figure 3.3, light-colored lines represent one standard deviation.
3.2.3 Miniature Antennas

Patch antennas provide half-space isolation by virtue of the substrate ground plane, a feature lacking in other antenna types such as loop antennas. The effects of a high (and variable) permittivity superstrate on patch antenna resonance and feedpoint impedance become more pronounced as the frequency of operation is pushed higher in order to reduce antenna dimensions.

Dielectric resonators ("pucks") rely on a large difference between puck permittivity and that of its surroundings to function without excessive loss. The high relative permittivity of the skin ($\varepsilon_r \approx 40$) and other tissues (e.g., blood, fat) surrounding the dielectric resonator obviates the high "permittivity contrast" required by the resonator to operate properly.

Research is currently ongoing within our group to assess the suitability of Planar Inverted F-Antennas (PIFA) and loop antennas. Previous work on implanted antennas for pacemakers [112] (which adhere to the muscle layer, rather than the skin layer) found magnetic dipole antennas to be effective. Magnetic antennas are of particular interest as electric antennas experience higher tissue loss.
3.3 Power

The imperative to reduce size eventually bumps up against the physical principle that energy is required to do useful work. We need to take a high-level look at what work the system needs to perform, how much of that work the implant needs to perform and then the details of how that implant can perform that work the best it can with the available energy.

The implants’ dimensional constraints have a negative impact on antenna performance and energy resources. An inefficient antenna operating in a lossy medium allows only some small fraction of the driving power to escape the medium as electromagnetic radiation, giving very small return for the power invested in a transmission. Multi-year longevity requires that the device’s average power consumption be reconciled with the power source’s energy capacity. Some implants work around a limited power supply by providing external power through inductive coupling [9, 113, 114] or communication schemes such as absorption modulation [115]. These approaches are not feasible for this project, which requires careful selection and management of a primary cell. Methods for scavenging energy from the environment are also examined.

3.3.1 Efficiency Metric

The core requirement of communicating identification provides a good focus point for system design. The energy that performs this fundamental work is the energy contained in the radiated electromagnetic field, which transports the required information. A measure of tag efficiency is given by:

\[ \eta_{\text{tag}} = \frac{P_{\text{rad}}}{P_{\text{pos}}} \]

Where \( P_{\text{pos}} \) is the maximum power extractable from the power source and \( P_{\text{rad}} \) is the energy successfully delivered into the radiated field, which successfully accomplishes the required communication.
Techniques for maximizing this metric are discussed in Chapter 4 and elsewhere. Being ever mindful of this over-arching metric aids in trimming unnecessary consumption and resolving occasional compromise choices.

### 3.3.2 Duty Cycle

A fundamental approach to energy efficiency is to supply energy only when it is needed. Turning a light on when one enters the room and off when one exits is a simple example. It is not quite so simple for wireless communications systems, but the goal is the same: turn it off when you do not need it on.

Duty cycle is the fractional expression of the length of time a periodic event is “on” to the period between events. This is of particular benefit here, in that total energy output may be determined by using the duty cycle ratio to relate peak power consumption to average power consumption.

![Diagram of Duty Cycle](image)

**Figure 3.4 Power Duty Cycle**

The period between power events of duration \( \tau \) is the event repetition interval (ERI). The event repetition frequency (ERF) and ERI are reciprocals of each other. The average power consumption \( P_{\text{avg}} \) is given by

\[
P_{\text{avg}} = \frac{1}{ERI} \int_{0}^{ERI} P(t) dt
\]
which for the “square” wave shown in Figure 3.4 is given by \( P_{\text{avg}} = \frac{P_k \tau}{ERI} \).

A high-level tag function is often comprised of an overlapping sequence of lower-level functions, the energy costs of which are summed to provide an equivalent \( P_k \) for the complete duration of the high-level function to be used in determining that function’s total average power consumption. The concept of duty cycle is important not only for determining energy management at the tag but also for application in the signaling protocols to be used between tag and interrogator. The duty cycle of these communications impacts both tag and interrogator power consumption and is a regulatory requirement for most frequency bands.

### 3.3.3 Batteries

Using a primary cell as the power source means that the service life and energy capacity of the source are predictable, resulting in predictable device longevity. Through the development of a “power budget” the time-averaged energy costs for device activities can be weighed against overall system performance. These device activities may be dynamically adjusted to accommodate usage shifts or to enhance system performance when the power budget is being spent at less than worst-case rates.

The capacity of a primary cell generally diminishes when subjected to large current draws. For many liquid chemistries, this capacity loss is due to disruption of the passivation layer. Manufacturers generally rate batteries at a current draw which permits the transport of ions from the anode without disruption to the passivation layer. Increased current results in increased porosity of the layer, and high draws can disrupt the layer, leading to ion contamination of the cathode.

Exceptions include specialized chemistries such as Lithium Silver Vanadium Oxide (Li-VSO). Li-VSO batteries are used in implanted defibrillators, occupying about half of the volume available to the device. Defibrillators require a pre-charge phase of about 20 seconds, during which time high current draw (1 – 2 A) from the battery supplies a storage capacitor, which then delivers a high-power pulse to the heart [116]. Li-VSO batteries are expensive (nanofabrication techniques are used) and would require custom manufacturing to obtain a package size to fit our application.
The terminal voltage of various Lithium-based primary cells covers a range of 3 – 3.95 V. Other chemistries such as Silver Oxide have a terminal voltage of 1.55 V. Many electronic components are designed for supply voltages of 3 – 3.3 V, as was the case for several radio transceivers reviewed for this project. To obtain the rated specifications for power and sensitivity of an integrated receiver, its supply must not drop below 3 V.

We will design for batteries that cannot deliver current pulses of sufficient duration and magnitude to supply the electronics load without diminishing battery capacity. One approach is to provide a high capacitance across the batteries to supply transient high loads. The capacitor’s self-leakage current could be a major lifetime consumer of energy and must be carefully selected. Another approach is to use a switched capacitor and to charge it on demand. High current operations such as RF transmission and reception would require a pre-charge phase, allowing sufficient time for a low-current draw on the batteries to accumulate enough energy for the capacitor bank to supply the operation. Meeting range and longevity goals while running off a coin cell becomes plausible when the power budget is spent on sparse triggered transmissions of minimal duration and high power.

Duty cycle provides a useful metric for careful battery management. The battery’s realizable energy capacity is adversely impacted by constant current draws higher than the manufacturer’s rating. It has been shown for some battery chemistries that periodic pulse loading enhances capacity over constant draws, with low duty cycle loading being preferable. This charge recovery effect has been demonstrated experimentally in manganese-zinc, alkaline-manganese, lead-acid, manganese-zinc [117], lithium-ion and zinc-zinc oxide cells [118], [119]. This is not necessarily evidence that the chemistries of the coin cells being considered for this tag respond similarly, but lessens the reluctance to use pulse draws when an improved response time over “optimal” current draws is desirable.

Device activities such as transmission and reception demand currents well in excess of optimal draining currents and beyond the pulse current capabilities of many battery types. To accommodate this high-peak power, the repetition interval between such events should allow for an energy accumulation phase where an equivalent average
power may be drawn from the battery at safe current levels and capacitively stored to meet peak event demands.

For example, suppose a 3 V battery has a rated current of 0.2 mA. To accumulate enough energy to supply an event requiring 20 mA at 3 V for 10 ms (i.e., 600 μWs) without exceeding the 0.2 mA rating, 1000 ms of “charge-time” is required. Should the same battery be capable of 2 mA pulses, this ability could be used when a rapid pre-charge is desirable, such as when a Demand Poll (4.5.3.3) slot comes up quickly.

3.3.3.2 Shunt Capacitor Bank

A design using a “super-capacitor” (or “ultra-capacitor”) and silver oxide batteries is shown in Figure 3.5. A study by our group comparing the GW 209D to a tantalum capacitor bank of comparable capacitance shows that the super-capacitor is to be preferred for low duty-cycle loads. A parallel tantalum bank has a lower equivalent series resistance (ESR) but much higher leakage than a single super-cap. The volume required by the tantalum bank is more than double that of the super-cap, with individual tantalum package dimensions exceeding the height requirements of a “slim” design.

The design of Figure 3.5 is well suited to using silver oxide batteries, as the super-cap requires a balancing mechanism due to its dual-cell arrangement and its rather low voltage rating (4.5 V). With package dimensions of 28.5 x 17 x 2.06 mm, the GW 209D
is well suited to supplying an ID tag that uses a planar antenna and ground plane. Base package dimensions without batteries and antenna are shown in Figure 3.6.

![Figure 3.6 Supercapacitor Package (Depth: 17 mm)](image)

### 3.3.3.3 Switched Capacitor Bank

The architecture shown in Figure 3.7 converts a nominal 3 V battery terminal voltage to some higher value $\text{V}_c$ for storage at the capacitor bank. When the load is active, the capacitor bank supplies a low drop-out (LDO) 3 V regulator that drives the load.

Power losses result from converter operation, the self-discharge of the capacitor bank and regulator operation. The largest potential loss is energy that remains stored in the capacitor bank once $\text{V}_c$ drops below the voltage required by the regulator. The difference between the output voltage of the regulator and the input voltage required by the regulator is known as the drop-out voltage, which can be small (0.015 – 0.2 V) and is proportional to current magnitude. Assuming a 0.2 V drop-out, load operation should cease when $\text{V}_c = 3.2$ V. The energy $U_R$, which remains stored on the capacitor, is given by
\[ U_R = \frac{1}{2} CV^2 = 5.12C \ [\text{Joules}] \]

When \( C = 47 \mu F \), this amounts to 150 \( \mu C \) of charge (or 240 \( \mu J \) of energy) which will seep away through the capacitor's self-discharge. Designating the energy requirements of the load and regulator as \( U_L \), the capacitor must be pre-charged to an energy level \( U_C \) such that:

\[ U_C - U_R = U_L = \frac{C(V_c^2 - V_r^2)}{2} \]

Efficiency = \((V_r/V_c)^2\)

It is apparent that increasing \( V_C \) and reducing \( C \) results in less energy loss after the load is removed. Figure 3.8 shows \( V_C \) under a constant energy drain (i.e., a regulated load) with identical initial stored energy where \( C_1 = 0.5 C_2 \). The smaller capacitance / higher voltage system is able to sustain regulation longer, resulting in more energy being available to the load. Reducing \( C \) by a factor of 2 reduces wasted energy by a factor of 2. Component selection in boost converter design must take into account a capacitor's value, voltage rating and package size as well as regulator input voltage limits and conversion efficiency.

![Figure 3.8 Capacitor Bank under Constant Load](image)
The battery current used to charge the capacitor bank should adhere to the manufacturer's recommended current draw $I_B$ (typically 100 – 200 μA for Lithium coin cells). In order to supply large loads (e.g., 50 mA) a "pre-charge" period is required by the capacitor bank, during which sufficient energy to supply the load is drawn from the battery and stored in a more usable form.

For a fixed functionality design, the repetition interval of various tasks is decided by the power budget and the chosen task emphasis. An agile design which can accommodate shifting task emphasis and a time-evolution of task requirements is more efficient and more useful. Exploiting power savings from suspended tasks and accommodating short-term power overruns should be accomplished on-tag with a minimum of processing requirements.

3.3.4 Scavenged Power

The tag spends most of its time in Sleep mode, consuming just enough energy to keep a timer crystal oscillating. Although current consumption is very low (~1 μA) over a period of 5 years Sleep mode alone would consume 43.8 μAh. This figure can represent a very high percentage of a battery pack's power capacity, about 50% of the current prototype specifications energy.

Several approaches to scavenging ambient energy are available. Although their average power generation makes them inappropriate for many applications due to the low-grade energy generally available, the extremely low average power consumption of our tags mean these approaches merit consideration. We can ignore solar radiation but should consider vibrations, temperature gradients and pressure variations.

3.3.4.1 Temperature Gradients

Low-power thermoelectric generators exhibit a $15 \mu W/cm^2$ power density with a 10 °C thermal gradient [120]. Few sensor systems are in an environment that would expose Stordeurs' device to such gradients, but the possibility exists that a sub-dermal implant in a marine mammal could use this approach.
During a deep dive, the capillaries in the scalp of the sea lion are expunged of blood. Somewhere between the animal's brain (37 °C) and the sea water at 250 meters (≈ 0 °C) a relatively steep thermal gradient exists, which might be exploited by a thermoelectric generator. We would expect that at shallower depths, when the skin remains perfused with blood, such gradients would not penetrate the tissues deeply and would be much less effective as an energy source.

Assuming half of the battery volume allocated for the latest prototype was given over to a thermoelectric generator and exposed to a 10 °C gradient, an 8 µW source would be realized. Additional tag volume would be required for a secondary cell to store the sporadic energy surplus obtained during a dive, as well as the power conversion and management circuitry necessary.

Determining the viability of using thermal gradients requires more data, specifically the thermal gradients such a device would be exposed to during the animals' normal activities. Such a study could be conducted by outfitting a sub-dermal tag with appropriately located thermal sensors.

### 3.3.4.2 Pressure Gradients

Once weaned, marine mammals dive to forage for food. This reliable behaviour may be exploited as a source of power for the device. Routine dives occur at depths of between 5 and 150 metres, and dives of up to 350 metres have been recorded by biologists.

Again, allocating half the battery space to a pressure generator, a surface area of 180 mm^2 with a potential stroke of 4mm exposed to 100 PSI is subject to a force of 12.7 kg. Full stroke work is 50kJoules or enough to supply 1uW for 14 hours. A single dive could supply Sleep mode power consumption for half a day; sea lions make around 17 dives per hour while foraging.

This exciting possibility deserves further research and development.

### 3.3.4.3 Vibrations

This approach converts mechanical movements into electrical energy. A common example is a wristwatch that doesn't require winding. Arm motions are converted into
enough energy to drive an oscillator. A similar mechanism that could supply the energy required by the Sleep mode would be great for this application.

A study by Roundy et al [120] has shown that piezoelectric conversion is superior to electrostatic conversion for a wide range of vibration types. Energy densities of 259 uW/cm^3 are realizable. However, the amount of energy available correlates directly with the vibration characteristics. Such characterizations could be determined with a telemetry device equipped with accelerometers attached to a sea mammal.

3.4 Summary

Antenna design remains crucial to attaining system efficiency and adequate range. A tuning mechanism appears to be critical. A dual DC-DC conversion is desirable for efficient transceiver operations without killing the batteries. This conversion is best attained by pre-charging a high voltage capacitor bank to be discharged by the transceiver through a switched regulator. Energy scavenging, in particular using the pressure changes from sea lion foraging dives, is an exciting avenue to pursue.
CHAPTER 4 Architecture Alternatives

This chapter presents four general system architectures following an assessment of operating frequency choices and a word about network topology.

The first, Blind Transmit, is a simple pinging tag.

The second, Pulse Triggering, uses trigger pulses from an interrogator to activate a passive or semi-active (i.e., low duty-cycle) detector on the tag. An inefficient antenna combined with detector mismatch (due to the impact of tissue changes on antenna characteristics) makes the tightly constrained space of a subcutaneous implant a poor environment for this approach. However, other application fields such as externally mounted animal telemetry, inventory management, security and industrial sensing might make use of it.

The third approach, Single Channel Sharing Hybrid (SCSH), has a tag periodically monitoring the channel for an interrogator communications packet. The communication of data sets more complex than identity and mortality is now possible, as is a flexible and robust behavioural command set. Although not fully described here, an intriguing possibility is for a tag to pose as an interrogator and record grouping behaviours when it is absent from a monitored locale. The use of a pilot signal from an interrogator is also discussed as a system performance improvement and possibly as a mechanism for dynamic antenna tuning.

The fourth approach, Single Channel Sharing Hybrid with Networked Interrogators (SCSH/NI), holds the best promise for system performance when tag communications range is low, as well as potentially significant savings in interrogator costs. Small and inexpensive, the interrogators form a self-organizing network when installed on site by field personnel. Coverage of complex geographies is accomplished without comparable shadowing and makes close range communications possible throughout the locale.
4.1 Frequency Selection

The European Telecommunications Standards Institute (ETSI) provides regulation for European countries such as Great Britain, France and Germany; the Federal Communications Commission (FFC) does so for the U.S. and Industry Canada for Canada. The Comisión Interamericana de Telecomunicaciones (CITEL) is an entity of the Organization of American States (OAS), which coordinates regional telecommunication efforts for our hemisphere.

Semiconductor manufacturers attempt to serve all markets, so many transceivers can operate in both European and North American ISM bands. Our application needs to operate in both Canadian and American jurisdictions, so we face the challenge of finding a regulatory common ground between the two.

We will consider the spectrum bracketed by the ISM bands at 40.66 – 40.70 MHz and 902 – 928 MHz, inclusive.

4.1.1 ISM Bands

ISM (Industrial, Scientific and Medical) bands are license-exempt bands that allow continuous transmissions. CITEL provides a listing of ISM bands that may be available in our region, although national regulations must be consulted. This listing is provided in the International Table of Frequency Allocations contained in the Radio Regulations (Volume 1) Articles RR S5.138 and S5.150 [121] and is reproduced in part in Table 4.1.

Unfortunately, the 433.92 MHz ISM band does not exist in Canada or the U.S. The 2.45 GHz band is the only worldwide allocation of spectrum for unlicensed usage without any limitations on applications and transmit duty cycle. North American operation in the 915 MHz and 2.45 GHz band (under Section 15.247 of the FCC Code of Federal Regulations (CFR) 47 and under regulations RSS-210 and RSS-219 in Canada) allows for transmit powers of up to 1 W (30 dBm), but this is rare in integrated transceivers. Although achieving greater than 10dBm transmit power in a low-cost system on chip is feasible, it is economically disadvantageous [122]. Applications at 2.45
GHz intended for European use would also require additional expensive filtering to make out-of-band emissions comply with European regulations (ETSI EN 300 328).

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Centre Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.765 – 6.795 MHz</td>
<td>6.780 MHz</td>
</tr>
<tr>
<td>13.553 – 13.567 MHz</td>
<td>13.560 MHz</td>
</tr>
<tr>
<td>26.957 – 27.283 MHz</td>
<td>27.120 MHz</td>
</tr>
<tr>
<td>40.66 – 40.70 MHz</td>
<td>40.68 MHz</td>
</tr>
<tr>
<td>433.05 – 434.79 MHz</td>
<td>433.92 MHz</td>
</tr>
<tr>
<td>902 – 928 MHz</td>
<td>915 MHz</td>
</tr>
<tr>
<td>2.4 – 2.5 GHz</td>
<td>2.45 GHz</td>
</tr>
<tr>
<td>5.725 – 5.875 GHz</td>
<td>5.8 GHz</td>
</tr>
</tbody>
</table>

Table 4.1 Frequency Bands Possibly Available for ISM Applications

Full power operation at 915 MHz and 2.45 GHz requires the use of spread spectrum modulation (DSSS or FHSS only). This modulation approach is expensive to implement and places severe requirements on the antenna design. There is no European 915 MHz ISM band; European ISM bands are allocated at 868 – 868.6 MHz and 433.050 – 434.790 MHz. Lower frequency ISM bands provide larger antenna aperture than the 2.45 GHz band, so for a given transmit power, receiver sensitivity, data rate, and reliability level they provide greater range.

4.1.2 Unlicensed Operation
Unlicensed operations in other parts of the spectrum are generally restricted in power level, duty cycle and application. National bodies provide details regarding this usage. The implanted tag may see use in both Canadian and American jurisdictions. Practically speaking, the SCSH/NI system would use the 915 MHz ISM band for NI communications, but this frequency may prove inappropriate for tag operations.

The FCC makes a special allotment for wildlife telemetry in the 40.66 – 40.70 MHz ISM band and 216 – 220 MHz band with a 1kHz bandwidth limitation. Transmit powers of 10 mW are permitted for terrestrial tracking, while 100 mW is permissible for
ocean buoys (which share the same allotment). A case might be made for using the higher power levels for marine mammal tracking. Industry Canada allows for much higher power levels in the 40.68 MHz ISM band (233 000 µV/m @ 3m) and allows 100 mW transmit power in the small band 216 – 217 MHz.

The FCC makes much of the spectrum available for use under stringent duty cycle and power level requirements. Figure 4.1 shows the allowable field strengths under two regimes: FCC 15.231 allows polling of devices (<2 s polling / device / hour) but periodic transmissions at predetermined intervals (e.g., “pinging” tags) are not allowed; they are required to operate under FCC 15.232 at much lower field strengths.

Assuming an antenna gain of one, field strengths may be converted to transmitter power levels using $P = 0.3 E^2$.

It appears that the best candidate frequency bands are the 915 MHz ISM band and 216 – 217 MHz. Antenna performance might decide this, along with the availability of COTS products or custom IC design. Certainly the NI portion of the SCSH/NI architecture will use the 915 MHz band.
4.2 Medium Access Protocol Design

The overriding consideration for our application is energy efficiency. Collision avoidance is part of that, as collisions are wasted transmissions that require re-transmission. Wasted transmissions are also those that do not reach their intended audience, meaning our MAC protocol must provide a high confidence link. Traffic that does not directly satisfy the information transfer requirements of the application layer must be minimized. These considerations serve to reduce energy spent on transmissions, but we must also reduce the energy spent used operating the tag receiver by minimizing receive events.

4.2.1 Network Topology

A network topology of a single master device communicating directly with a number of slave nodes is known as a star network. The limited range of the master/slave (interrogator/tag) radio link constrains wireless star network coverage to an area local to the interrogator. The star network topology describes the tag/interrogator relationship for all architectures.

While a device’s effective radiated power is ultimately limited by government regulation, standard specifications (and therefore semiconductor manufacturers) may stipulate much lower radiated power levels to enable frequency re-use by lessening
device range. The radiated power of the implanted tags (and therefore network coverage) is subject to limited battery power, antenna inefficiencies, tissue losses and a strongly interfering propagation channel. A goal of our design is to maximize the peak radiated power of the tags as part of attaining our range design goals. An interrogator does not have the size and power constraints that a tag does, allowing us to off-load complexity and requirements from the tag to the interrogator and serving to further reduce tag size and to increase tag longevity and network range.

Figure 4.2.2 SCSH/NI Topology

Extending the range of this network without imposing additional resource demands on the tags would require the use of additional interrogators. Figure 4.2.2 shows the Single Channel Sharing Hybrid with Networked Interrogators (SCSH/NI) topology. Tags are connected to interrogators in a star topology while interrogators form as close to a mesh network as they can.
4.2.2 Contention-Based

Contention-based tags may be broadly classed as those that attempt to sense the channel to avoid collisions (some variation of CSMA) and those that blindly transmit without regard to channel occupancy (similar to ALOHA).

To sense the channel, an RF receiver is required. Those that blindly transmit require only a transmitter. There are advantages and disadvantages to both approaches; which is better depends on the design weight given to metrics such as reporting availability, cost and range. Receiver implementation is further complicated by PHY layer capabilities including antenna bandwidth, signaling methods and component performance.

4.3 Blind Transmit

A simple approach is to abandon duplex communication and create a tag that is a transmitter only. This could be thought of as a type of single-channel ALOHA. A key advantage to this approach is that it facilitates the use of a power amplifier, with corresponding range gains.

![Figure 4.3.1 Blind Transmit PHY](image)

Power consumers on the Blind Transmit tag (Figure 4.3.1) would be a timer, a temperature sensor that would be periodically sampled to monitor mortality, possibly a pressure sensor to suppress transmission while the animal is submerged and the RF front-
end. Difficulties in implementing this PHY layer arise in the antenna, capacitor bank and RF front end.

Communications for this tag relieves the interrogator of the requirement of transmitting to tags. Given the potential regulatory restrictions on interrogator transmissions, this is an important point. Normal use of North American ISM bands allows full power (1 W) transmissions only when spread spectrum modulation is used, and while use of other bands might allow higher peak powers, the duty cycle must be very low, which acts contrary to the low latency outcome desired of interrogator signaling.

4.3.1 Spread Spectrum

Should an agile antenna tuning mechanism be implemented, FHSS could be used for this tag. As FHSS is a synchronous protocol, interrogators would be sorely pressed to catch a transmission.

4.3.2 Pulsed Carrier

A related approach is the use of pseudo-orthogonal pulse trains as identity codes. A commercial product using this approach accommodates 212 tags per channel [123]. There are 33 fully orthogonal Gold codes in a 511-bit maximum sequence code, which provides for 132 unique codes when used forward, reversed, inverted and non-inverted [66]. The use of a single frequency relieves requirements for antenna tuning on the tag and signal processing on the interrogator. However, as the number of tags increases lengthier codes would be required to provide each tag with a unique, orthogonal code. As reporting intervals increase with code length increases, pre-scaling this approach to handle many tags would diminish system performance.

This approach is attractive because an efficient (Class C, D, E, etc.) amplifier may be used with the microcontroller gating the carrier (using on-off keying (OOK) or amplitude shift keying (ASK) modulation), allowing for direct control over packet duration. Longevity of the device could be directly specified, thereby establishing known reporting intervals.
4.3.3 Mitigating Collisions

The opportunity for collisions is in fact very small. Assuming an ID transmission has a duration of \( \approx 1 \text{ ms} \) and a reporting interval of 40 s, the active duty cycle is 0.0025\%. With a random temporal distribution of tag reporting events, a very low probability of synchronous reporting exists.

We might expect a random temporal distribution for several reasons. The tag timers are not started simultaneously. Even if they were, timer crystals exhibit different frequency tolerances (+/- 20 ppm), stability over temperature (+/- 30 ppm) and aging drift (+/- 5 ppm). Colliding tags may well have timers running at sufficiently different frequencies so that subsequent reports would not collide.

We can further reduce the chances of subsequent collisions by programming tags with slightly irregular reporting intervals. For instance, assume two-byte, non-orthogonal ID codes (about 65,000 tags). Designate the ID bytes as \( B_1 \) and \( B_0 \). Any number of schemes may be implemented to accelerate synchronous reporting divergence, for example:

\[
T_{N+1} = T_{\text{base}} + \frac{B_1}{255} \sin \left( \frac{2\pi 128}{B_0} N \right)
\]

This scheme provides a family of reporting interval sinusoids of varying amplitude and phase that diverge from \( T_{\text{base}} \) faster than by timer drift alone. Such a function could be implemented in firmware using look-up tables and would demand tweaking according to \( T_{\text{base}} \) for a given system.

4.3.4 More PHY Layer

While high power is desirable for range, regulations may preclude high power use except for devices that use spread spectrum modulation. This is an unpleasant if not impossible option for this device due primarily to antenna bandwidth requirements as well as cost and complexity.

Capacitor bank design critically depends on transmission duration; volume requirements present problems for both super-capacitor designs and more conventional capacitor use.
A conventional capacitor bank could be primed at a higher voltage than a super-cap (requiring the use of a voltage regulator to drive the RF front end) and would lose its remaining energy to self-discharge once the regulator dropped out of regulation.

A super-cap has a much lower voltage rating. No regulator is required; the RF front end must run at battery voltages, and continuous self-discharge of the super-cap occurs over the device’s lifetime.

4.3.5 Summary

Blind transmit tags have the potential to provide high power, short duration ID transmissions. Tag longevity would be known.

Another advantage to this approach is a drastic reduction in interrogator power use and complexity, with correspondingly lower costs in design, manufacturing and operation. The interrogator would constantly monitor for channel activity on one or more tag channels, acting solely as a receiver, thereby alleviating regulatory concerns regarding fixed station emissions.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Power Transmissions</td>
<td>Inflexible Functionality</td>
</tr>
<tr>
<td>Short Duration Transmissions</td>
<td>One-way Communication</td>
</tr>
<tr>
<td>Predictable Longevity</td>
<td>Peak Power Regulatory Concerns</td>
</tr>
<tr>
<td>Reduced Interrogator Costs</td>
<td>Sparse Reporting</td>
</tr>
</tbody>
</table>

Table 4.2 Blind Tag Balance Sheet
4.4 Pulse Triggering
Transmissions are wasted if they are not cleanly received by an interrogator. One method of providing collision-free, orderly reporting in proximity to an interrogator is through a pulse trigger. A triggering beacon from the interrogator serves two purposes: to trigger a tag response if appropriate and to provide synchronization for orderly (i.e., no collisions) reporting. The trigger beacon is followed by a number of fixed duration time slots, with each tag assigned a unique time slot.

![Figure 4.4.1 Trigger Beacon TDMA](image)

Identification information is not encoded in the reply transmission but only *when* that transmission occurs. A tag is noted as present when the interrogator detects a signal in the corresponding time slot. This approach allows tag transmissions to be extremely simple (e.g., carrier only) and of very short duration. Peak power levels of such transmissions may be very high while the transmission itself consumes very little energy.

For a given noise floor, the demodulation of a signal requires a greater signal-to-noise ratio (SNR) than does the detection of a signal. The SNR required for detection is chosen according to what is acceptable. For the interrogator, the range at which very weak tag signals may be detected would benefit from an approach using a heterodyned receiver (to reduce the noise floor) and a square-law detector. The range obtained using such a detector could be twice the range obtained with a system requiring demodulation of the received signal. Matched filtering and other signal-processing techniques [124] would further enhance range performance.

However, the tag cannot afford the energy costs of constantly running a receiver in order to detect a trigger beacon. The ideal solution from a power management
perspective is the use of passive detectors that require zero power to operate [125]. The majority of the power budget is now available for transmissions.

4.4.1 Passive Detector

RFID tags use a detector (i.e., a diode) to rectify an interrogator signal that provides enough energy to power the tag electronics. This requires significant interrogator radiation energy densities, which is one reason why RFID is very short range. The intent of a trigger beacon in our case is not to power the tag but to provide a CMOS voltage level transition that would trigger a passive interrupt port on the microcontroller.

![Graph: Detector Square-Law Response](image)

**Figure 4.4.2 Typical Detector Square-Law Response [126]**

Full realization of this goal presents several difficulties, resulting from the high input power levels required by a passive detector (Figure 4.4.2). These difficulties may be solved by a brute-force approach, requiring a very high power trigger beacon pulse from the interrogator. As a guideline to ensure the health of animals near the interrogator, we refer to the IEEE Standard for Safety Levels for human exposure to RF [127], which indicates an average power density of 3.05 mW/cm² for 915 MHz signals. A trigger beacon may have an arbitrarily small duty cycle, so this average power density can easily be accommodated by increasing the trigger beacon interval as necessary. However, it has been shown that pulses as short as 10 ns with field amplitude greater than 1 W/m are
hazardous to biological tissue as they can cause membrane phospholipid rearrangement and activation of the effector enzymes of apoptosis [128].

The power levels at the detector are attenuated by the front-end mismatches (antenna to channel and detector to antenna), switch insertion loss, antenna inefficiency, tissue losses and propagation losses. As tissue characteristics change due to animal growth and/or diet, the antenna becomes de-tuned. This detuning is both a resonance shift and an impedance shift. Mechanisms for re-tuning the antenna must also consider the match with the detector [129, 130], as the maximum power transfer theorem applies.

A common microwave detector is simply a Schottky diode, which can act as a power detector even without a DC bias [130]. With proper care in the impedance matching of the detector, a Sallen-Key filter (implemented with a sub-microamp operational amplifier) provides a low noise envelope detector of interrogator transmissions. The MSP430 microcontroller series from Texas Instruments (among others) provides port edge transition interrupts, which means a hardware interrupt is available when running in very low-power modes. Detected interrogator pulsed transmissions would provide these transitions. The continuous operation of this detector/mcu arrangement consumes less than 2μA at 1.8V, or about 95 mAH over a three-year period.
4.4.1.1 Passive MAC Protocol

The simple transmission triggering of the passive detector is shown in Figure 4.4.3. It is assumed that the PHY layer implementation uses high peak power transmissions and that the battery is unable to source the pulse power required. The capacitor bank used to accumulate sufficient energy for the transmission must be charged once a trigger beacon has been detected. System operation is as follows:

- The passive tag periodically samples the temperature. Trigger beacons received during sampling are ignored.
- If sufficient charge for a transmission is not present on the capacitor, the system initiates or continues the charging process.
- If sufficient charge is present, a transmission occurs in the assigned time slot.
- Mortality is indicated by continued beacon responses.
- Live animal tags inhibit beacon response and sensor sampling for 15 minutes, then return to the sleep state.
4.4.2 Cycled Active Detector

As a completely passive detector is unlikely to provide adequate range without the use of a very high power trigger (with the associated expense and potential hazards), a compromise is to use duty-cycled active devices for detection. A low noise amplifier (LNA) – active detector – filter – conditioning receive chain would serve to boost detector range (Figure 4.4.4).

![Detector PHY](image)

Figure 4.4.4 Detector PHY

Similar approaches to providing a low-power “wake-up” radio have been proposed for use with PicoRadio [131, 132] and the Prototype Embedded Network (PEN) [133] (nee Piconet [134]) under development at the University of Cambridge and the Olivetti and Oracle Research Laboratory until 2002 [135, 136].

Amplification and active detection must operated with a low duty cycle. As it is hypothesized that animal movements and obstructions may render valid communication windows fleeting, we attempt to provide the illusion of always-on operation by using high-frequency “on” times. To achieve both a low duty cycle and high frequency operation, the “on” duration must be as small as possible. After a triggered ID transmission, the device will inhibit any further transmissions according to the applications’ minimum required reporting interval. This period of response inhibition is known as Hibernation mode and is of duration $T_H$. 

63
To cleanly detect a beacon pulse, the detector “Listen” duration $T_L$ must be:

$$T_L \geq NT_S + 2T_B$$

where $N$ is the number of reporting slots, $T_S$ is the reporting slot duration and $T_B$ is the beacon trigger duration. With a fixed amount of battery $P_L$ allocated for the Listen event, the number of Listen events $N_L$ is given by

$$N_L = \frac{P_L}{P_{Lavg} T_L}$$

where $P_{Lavg}$ is the average power consumed during a Listen event.

$$T_{LI} = \frac{T_{life}}{N_L} = \frac{T_{life} T_L P_{Lavg}}{P_L}$$

For a device longevity of $T_{life}$ the nominal interval between listen events $T_{LI}$ is given by:

Figure 4.4.5 Active Listen Duration

Figure 4.4.6 Detector Listening Mode
The nominal interval is the worst-case design for a tag that never actually transmits an ID. When a tag does transmit an ID the device enters Hibernation mode, suspending Listening mode for $T_H$.

![Diagram](image)

Figure 4.4.7 Hibernation Mode

The energy normally expended while Listening is conserved. The power $P_T$ expended in an ID transmission is offset by the power saved during hibernation $P_H$ where:

$$P_H = \frac{T_H}{T_{LI}} P_{\text{per active listen}} = T_H P_{\text{avg}}$$

For example, with $T_{LI} = 20$ s and $T_H = 15$ min, 45 Listen events are “saved.” If $P_T < P_H$, a net energy gain allows for some reduction of $T_{LI}$ in subsequent operations.

Substantial reductions of $T_{LI}$ may be obtained through the use of sensors (e.g., pressure and temperature) to suspend Listening when the target species is at sea. Steller sea lions may spend about 20 hours foraging at sea followed by an equivalent time spent ashore [137]. Suspension of Listen events during foraging could cut Listening power requirements nearly in half; these power savings could be used to reduce $T_{LI}$, increase sensor sampling, extend device longevity or any combination thereof. Sensor sampling may be easily accommodated in a power budget by suspending Listen events long enough to cover the sampling costs.
4.4.2.1 Scalability

An essential consideration of this system approach is that of scalability. Fixing the number of reply slots at N to establish $T_L$ means that $T_L$ is unnecessarily long when the actual number of tags is less than N. Once the number of tags is equal to N, the system is saturated and cannot accommodate more tags. This problem of scalability makes this MAC implementation less than ideal for systems that do not have a fixed number of active tags.

To work around this and introduce scalability, more information may be carried in the trigger beacon signal. A series of coded pulses could be used to signify different tag batches. With an initial “wake-up” pulse and a final synchronization pulse, some intermediate pulses could be used to encode the batch number. These intermediate pulses are analogous to shifting the least significant bits (LSBs) of tag IDs into the beacon “batch” address pulses. For example, dividing the tags into four batches requires two Batch ID bits (Figure 4.4.8).

![Figure 4.4.8 Addressing $2^n$ Batches](image-url)
When implementing this solution we should attempt to minimize $T_L$. The average power consumption of listening $P_{\text{avg}}$ remains unchanged if $T_L$ is reduced by a factor of two and the interval between Listen events $T_{\text{Li}}$ is also reduced by a factor of two. However, the frequency of Listen events is doubled, which provides improved system response to transient windows of exposure to interrogator signaling. Animal behaviours (e.g., head movements) might present small windows of opportunity for detection, while aerial surveys present inherently transient communications windows. In minimizing $T_L$ ($T_L \geq N T_S + 2T_B$) we should examine the relationship between beacon duration $T_B$ and slot reporting duration $T_R$.

Assume that an interrogator pulse and a tag reply slot are of equivalent duration $T_S$, and set an upper limit of $2^{14}$ tags (i.e., 16,384 tags). This “upper limit” on the number of tags may be chosen to be $2^N$ for some arbitrary $N$ as the result of the following discussion directly generalizes to $2^N$ tags, but for clarity we will choose $N = 14$. Now evenly split the $2^{14}$ tags into $2^n$ batches, each with $2^{14-n}$ tags. For example, with $n = 1$ we get two batches of $2^{13}$ tags and reduce the slot reporting duration per batch to:

$$T_R = T_P(2^{14-n}).$$

The number of Batch ID bits required is $n$. As each beacon slot requires two fixed pulses (wake-up and synchronization), the beacon duration is:

$$T_B = T_P(n + 2)$$

$T_L$ must span two beacons and one slot reporting duration, so:

$$T_L = 2T_B + T_R = T_P(2n + 4) + T_P2^{14-n} = T_P(2^{14-n} + 2n + 4)$$

$T_L$ is minimized for $n = 12, 13$ ($T_L = 32 T_P$) and only is a single pulse duration longer ($T_L = 33 T_P$) for $n = 14$, which we will consider negligible.
This result indicates that to introduce scalability into a triggered TDMA system, active listening is (effectively) minimized by addressing each reporting device individually. The system now uses a polling approach.

Interrogator polling in a descending sequence allows a tag to monitor the current polling address, calculate the number of polling frames until its address comes up and return to a low power state. When the tag expects its number to be called, the receiver is activated again to monitor the next poll and respond with a transmission as appropriate. After a transmission, hibernation mode is entered and receiver operation is inhibited for $T_H$.

Mortality is indicated by not entering hibernation mode and responding continuously to polls as frequently as the capacitor bank pre-charge allows.

4.4.2.2 Cycled Detector Protocol

![Cycled Detector State Transitions](image)

Figure 4.4.9 Cycled Detector State Transitions
4.4.3 Contention Summary

Fixed participant systems should be implemented using passive detectors and powerful trigger pulses of a very low duty cycle and low repetition rate. Peak power levels required to activate distant tags in old animals are likely to be prohibited by regulatory bodies and may be hazardous to biological tissue in close proximity. This approach is more appropriate for short-range applications with highly efficient free-space antennas, with a corresponding decrease in peak trigger power levels.

Scalable systems should be implemented using cycled active detectors and per-tag polling by the interrogator. As the beacon content is effectively an addressed packet, this approach may be more easily implemented using an active receiver with the reduced noise floor available through reducing bandwidth with integrated mixers and filtering. To provide high-power, low-energy reply pulses the transmit chain and receive chain must remain distinct, precluding the use of COTS transceivers.

Blind transmit tags would provide powerful transmissions at regular intervals, resolving any low-probability collisions by retransmission on slightly skewed timebases. The collision-free triggered transmissions of a passive detector tag require high-power trigger pulses and exacerbate the antenna tuning problem, with the addition of detector tuning requirements. The best performance of a cycled active detector is attained when an addressed poll is embedded within the trigger beacon.
4.5 Single Channel Sharing Hybrid (SCSH)

The incorporation of half-duplex operation dramatically increases tag utility. Data telemetry from a sensor payload may be communicated and the interrogator is able to dynamically alter tag behaviours and functionality to meet user priorities or adjust to evolving system behaviours. In addition, system housekeeping chores such as clock correction and reporting of tag power information may be accomplished.

Data transfer over a contention-free radio link consumes energy in direct proportion to the amount of data traffic and link overhead required. The protocols developed here provide for ID reporting, behavioural modification and data transfer, with a sharp focus on minimizing the tag energy required to accomplish the task. Let us reestablish the context for these communications.

4.5.1 Latency and Throughput

As Steller sea lions mature, their attendance patterns at haul-outs changes. Pups may spend 22 hours ashore [138] while mature animals may forage for a day (20 – 25 hours) and remain ashore for a similar period (23 – 27 hours) [137-139].

ID reporting every 15 minutes provides a relatively fine-grained attendance profile, facilitating behavioural analysis. Sensor data gathered while the animal is at sea is of more interest than data gathered when the animal is lounging ashore, so a rough first approximation of sensor telemetry requirements is a single data set every two days.

![Figure 4.5.1 Crude Attendance Pattern](image)
The many hours spent ashore implies that throughput latency is a non-issue. Fixed interrogator installations allow tags to relate data sets essentially at their leisure. This is critical to the capacitor bank specification as the energy required for transmitting a single large data set greatly exceeds the energy required for an ID transmission; allowing capacity for lengthy transmissions results in wasted energy left in the capacitor bank when a shorter transmission is required.

4.5.2 Interrogator Broadcasts

Interrogators and tags share a single channel. The interrogator alternates between transmitting broadcast packets and receiving in order to hear any tag replies. The tags periodically activate their receivers to Listen for an interrogator broadcast. Any tag that cleanly receives a broadcast packet switches to transmit mode and transmits a reply packet containing tag identification, status information and possibly a data transfer request. Tag Listen events are of duration $T_L$ and occur at intervals of $T_{LI}$.

Preferred interrogator operation is near-continuous transmission of a broadcast packet to which any tag will respond. The interrogator transmits a broadcast packet, switches to receive mode, listens long enough to determine that there is no incoming packet, switches back to transmit mode and repeats the sequence. For convenience this is referred to as Free Scan (FS) mode.

![Free Scan Mode Diagram](image)

Figure 4.5.2 Free Scan Mode
In Figure 4.5.2, $T_{FS}$ is the duration of an FS packet, $T_{TXR}$ is the time required by the transceiver to switch from transmit to receive mode, $T_s$ is the time spent in receive mode and $T_{RXTX}$ is the "turn-around" time required to switch from receive to transmit mode. The tag must be able to sense the interrogator carrier in time $T_{CD}$. System performance is critically tied to the tag Listen duration $T_L$ determined by:

$$T_L = T_{TXR} + T_s + T_{RXTX} + T_{CD}$$

$T_s$ (or "Sniff" time) is determined by allowing for the tags' $T_{RXTX}$, the interrogators' $T_{CD}$, round-flight propagation delay (20μs for 3km) and a slop factor of 1.2. Figure 4.5.3 shows a tag entering proximity to an interrogator, entering Listen mode when the timer $T_{LI}$ expires, detecting an interrogator broadcast packet and replying. The interrogator detects the incoming reply packet, extends reception for the complete packet and replies with a command packet CMD.

![Figure 4.5.3 1D Report](image-url)
4.5.3 Contention

An animal emerges from the sea. The tag awakens to Listen for an interrogator, transmits an ID code, receives a command packet and then shuts off for 15 minutes.

As this design attempts to minimize the Listen interval $T_{LI}$ to the 2 – 5 second window required by aerial surveys [66], random access collisions could occur only when multiple tags arrive in proximity to the interrogator in less than $T_{LI}$ and also happen to have Listen interval timers that expire during the same <5 ms window. The probability of several tagged animals presenting to an interrogator in the same 5 second time window is in itself arguably low; supposing a Listen duty cycle of 0.1% (e.g., $T_L = 5$ms, $T_{LI} = 5$ s) up to 1,000 tags could report without colliding in the same 5 second window. Tag timers are uncorrelated, so in the case of several “fresh” tags arriving near-simultaneously there is a low risk of transmission collision.

With a finite number of tags at the haul-out, an interrogator can schedule data set reporting by tags so that multiple tags having telemetry to transfer do not contend for the channel. A newly arrived tag transmits an ID (requiring a few milliseconds, PHY layer dependent) and then shuts off for 900,000 ms (i.e., 15 minutes). The tag transceiver duty cycle while ashore is around 0.001% (e.g., 9 ms / 900 s).

Vast spans of dead air exist during the hours that tags are present; data sets may be gradually relayed using very small packet sizes over extended periods of time. This approach minimizes capacitor bank inefficiency (or complexity) resulting from greatly differing transceiver power requirements for the Listen, ID Transmit and Data Transfer functions.

Three modes of operation are used to deal with collisions. These modes are identification only (IDO), implied polling (IP) and demand polling (DP).
4.5.3.1 IDO Operation

IDO prevents the tag from entering hibernation (typically 15 minutes). $T_{LI}$ changes slightly according to the method described in Blind Transmit: Mitigating Collisions. This mode essentially pretends the collided transmission never occurred and continues with normal Listen intervals. It is appropriate for tags recently emerged from hibernation (i.e., recent successful ID transmissions) and represents a low-energy, low-priority retry.

An IDO condition occurs when:

The CMD reply from the interrogator is corrupt,
The CMD demands IDO retries and
IDO is the default tag behaviour.

4.5.3.2 IP Operation

Figure 4.5.4 Tag IDO Operation

Figure 4.5.5 Tag IP Operation
Implied polling can be used to sort out a collision by using a TDMA approach similar to that used in **Passive Trigger**. The interrogator does not reply with a CMD packet and suspends transmissions. Each tag delays until its assigned timeslot arrives, transmits an ID packet and then monitors when the complete $2^{16}$ slot duration is over, allowing the interrogator to instruct tags as to subsequent behaviour. A carrier sense preceding the ID transmission should fail; if it does not, the tag attempts to receive a packet and switches to IDO operation should that fail.

### 4.5.3.3 DP Operation

![Figure 4.5.6 Demand Polling Operation](image)

Demand polling operation could be used in situations such as aerial surveys, targeted polling and system testing. A tag receiving a DP packet would calculate the offset to the DP packet specific to the tag and return to low power mode until that time.

This approach is most useful when the number of tags is small. Rapid cycling of per-tag polling is, of course, proportional to the number of tags addressed.

Although some confusion might result, the slot number for IP operation and DP operation should not be the same as the tag ID number. Equal numbers of ones and zeros are desirable in a tag ID to assist in the DC leveling of FSK systems. The sequence of assigned IDs should use binary representations that minimize correlation so that any chance of collision due to bit errors is reduced.

### 4.5.4 Capacitor Bank Requirements

In the absence of an interrogator, ideal Listen mode power consumption $P_L$ is:
\[ P_{LI} = P_{Lavg} \cdot T_L = P_{Lavg} (T_{TXRx} + T_S + T_{RXTx} + T_{CD}) \]

However, when an interrogator is present, to receive a complete packet the Listen power must accommodate:

\[ P_L = P_{Lavg} (2T_{FS} + T_{TXRx} + T_S + T_{RXTx}) \]

wasting \( P_{Lavg}(2T_{FS} + T_{CD}) \) for each Listen without an interrogator present. As \( T_{FS} \) > \( (T_{TXRx} + T_S + T_{RXTx}) \) this is undesirable and indicates \( T_{FS} \) should be as short as possible.

After receiving a complete packet, an ID transmission requires \( P_{TXID} \), sustaining transceiver operation during turn-arounds before and after \( T_{IDTx} \), and finally a CMD packet reception \( T_{CMDRx} \).

The power required by worst-case operation is:

\[ P_{WC} = 2P_{Lavg} (T_{FS} + T_L - T_{CD} + 2T_{RXTx}) + P_{IDTx} + P_{CMDRx} \]

Storing \( P_{WC} \) rather than \( P_{LI} \) is extremely inefficient. There are several ways to alleviate the situation, including the following:

- Drive routine Listen events directly from the battery. This limits battery choice.
- Store max \((P_L, P_{IDTX})\) and defer \(T_{IDTX}\) and \(Rx_{CMD}\) events by the charging time required to store max\((P_L, P_{IDTX})\).
- Implement two capacitor banks: one to store \(P_{LI}\) and one for \(P_{WC}\). A detection during \(T_L\) is followed by a pre-charge for \(P_{WC}\) and subsequent operation shown in Figure 4.5.7.
- Eat the loss and store \(P_{WC}\).

### 4.5.5 Eliminating \(T_{TxRx}\) and \(T_{RxTx}\)

A significant boost to tag power management is obtained by eliminating the dead air while the interrogator switches back and forth between transmitting and receiving. This crucial protocol adjustment has been noted elsewhere [140]. This can be accomplished with the use of two transceivers or a dedicated transmitter and dedicated receiver. The choice may be influenced by the use of proprietary transceivers for tag implementation.

The tag power savings are substantial \((\approx 50\%)\) and well worth the effort involved in interrogator design. The minimum duration of the interrogator receive interval must accommodate the time required by a tag to begin transmission after the end of an interrogator broadcast plus the time that transmission must be active to assure interrogator detection of an incoming packet.

### 4.5.6 Piloted Trigger

The single channel hybrid approach established that the Listen duration \(T_L\) directly limits system performance because the Listen interval \(T_{LI}\) must limit average Listen Mode power consumption to acceptable levels. Reductions in \(T_L\) result in a power savings that can be used to improve specifications such as reducing \(T_{LI}\), increasing sensor data collection rates and transmitted data payloads or extending device longevity.

Piloted triggering requires two channels. The pilot channel would be occupied by an interrogator transmission, which could be continuous or, in order to reduce average power should regulations require, operated on a duty cycle. Tag Listen mode would consist of a fast and power-cheap check of the pilot channel. \(T_L\) would be reduced from:

\[
T_L = T_{TxRx} + T_S + T_{RxTx} + T_{CD}
\]
Upon detection of a pilot, the tag switches to the second channel (monitored constantly by the interrogator) and transmits an ID. When the interrogator detects a carrier on the second channel (Ch 2), the pilot is suppressed. The interrogator responds to an ID with a CMD packet and resumes pilot operation unless a data transfer is granted.

![Figure 4.5.8 Piloted Trigger](image)

### 4.5.6.1 Collisions

Upon collision the interrogator suppresses the CMD packet and begins Demand Polling on the pilot channel. Tags not receiving a CMD packet monitor the pilot slot address, delay appropriately and transmit an ID.

### 4.5.6.2 PHY Layer

The abbreviated Listen Mode allows the transceiver to be directly driven by the battery. Capacitor bank storage requirements are simplified with respect to the Single Channel Hybrid and energy storage is also more efficient.
4.5.7 Data Transfer

When requested by the tag and approved by the interrogator, data transfer occurs in blocks using the $P_{WC}$ capacitor bank. The sequence is pre-charge, transmit block, repeat until transfer is complete. Data transfer requests will be denied by the interrogator when collisions have occurred or when the block size is too small.

As with the Single Channel Hybrid, a data transfer proceeds upon a tag request with interrogator approval. The block size is somewhat reduced as capacitor bank power is less, but reduced pre-charge intervals result in similar data throughput rates.

4.5.8 Summary

The Single Channel Hybrid MAC layer uses random access, with additional mechanisms such as IDO operation, IP operation and DP operation. Data transfers are accommodated. Device behaviours such as extended hibernation, $T_{LI}$ modifications and active testing are provided. The SCSH MAC protocol provides a mechanism for efficient tag power use.
4.6 SCSH with Networked Interrogators (SCSH/NI)

The realizable tag communications range will be limited both by the tag’s capabilities and by the geography where a system is situated. Rugged shorelines and rocky islands may make positioning an interrogator in an ideal location very difficult. An ideal location is one where a line of sight to all possible tag locations is available. Such a location excludes many haul-outs, resulting in less than ideal coverage due to potentially severe shadowing. The use of off-shore buoys is being considered for locations where vegetation or rocky obstructions severely limits land-based coverage.

Land-based installations may require the use of multiple interrogators to provide adequate coverage due to shadowing from land formations, inadequate tag communications range for the haul-out dimensions or some combination of the two. As base-station (i.e., single interrogator) installations may be bulky, expensive and difficult to install the use of multiple base-stations to provide coverage may be a non-starter. Antenna design considerations imply that the tag’s radiated field may be horizontally polarized, resulting in significant propagation losses as the sea lions are necessarily close to the ground. This would serve to lessen the communications range even further.

However, the application of energy-aware design techniques has the potential to resolve these issues. There is a middle ground between the extreme resource constraints faced by very small devices and the larger monolithic base-stations. Moderate sized, relatively inexpensive interrogators of limited range could provide multiple overlapping coverage areas, whereby short-range or shadowed tags will be covered (Figure 4.6.1).

Figure 4.6.1 Island Topology with Overlapping Coverage
Inter-interrogator communication of the networked interrogators would benefit from the power levels and multi-path mitigation available through the use of spread spectrum modulation. Interrogator network communications are invisible to the tags and require a distinct protocol for networked interrogators that we will call NI. The NI protocol will apply some techniques from the work done for low-data rate, low-power wireless sensor network protocols. Interrogator-tag communication will use the SCSH protocol while inter-interrogator communications will use the NI protocol; therefore, we will refer to this system architecture of layered protocols as SCSH/NI.

NI will:
- Allow field workers to add and move interrogators as necessary to:
  - Provide adequate tag coverage
  - Establish and maintain a single linked interrogator network
- Select an interrogator to aggregate and uplink periodic data reports
- Prevent tags with multiple coverage from becoming confused.

Figure 4.6.2 SCSH/NI Layering
Although tags would be blind to inter-interrogator communications, they may fall within the SCSH communications range of more than one interrogator. NI could implement a round-robin approach to ensuring only one interrogator conducts SCSH activity at any time. This not only keeps tag communications clean but reduces interrogator duty-cycle, thus enhancing longevity (Figure 4.6.3). Other NI modes of operation would include network discovery, CSH mode reporting, tag data aggregation and uplink transmission.

![Figure 4.6.3 NI: Round-Robin Polling and Tag Communications](image)

**4.6.1 PHY and MAC Layers in Brief**

Thionyl chloride-lithium cells have the highest energy density of all lithium-type primary cells and a service life of 15 to 20 years. A single D cell (Ø34 mm x 78 mm) provides 19Ah at 3.6 V with a nominal discharge current of 5 mA, while battery packs are available with capacities up to 800 Ah and 240 mA nominal discharge (Ø284 mm x 260 mm).

A portable interrogator with multi-year longevity is a viable option. Transceiver electronics must be able to service the modulation of the tag transceiver and to conduct
NI spread spectrum communications. A single omni-directional antenna would suffice as SCSH and NI communications can share the same spectrum.

The SCSH MAC protocol as presented implies near-continuous operation. This is not an absolute requirement, as periodic operation for a duration slightly exceeding worst-case $T_{LI}$ will register all Listening tags with a valid communications window. This result suggests that interrogators may be duty cycled at $T_{LI}/T_H$. Using some rough design guesstimates for these values of 15 s and 15 min respectively, an interrogator duty cycle of about 1.7% may provide system performance indiscernible from full duty cycle operation. Again, this assumes the premise that communications windows are not transient.

Concerns regarding transient communications windows diminish with the availability of multiple interrogators. Spatial diversity in interrogator placement can minimize signal fading due to obstructions and animal postures. As interrogator size and expense decreases more interrogators may be used per installation; spatial diversity and shorter range requirements resulting from an increased number of interrogators reduces duty cycle requirements, which in turn reduces interrogator size and expense. We should not pursue this process down to SmartDust dimensions, but allow the package size to be determined by accommodating an uncompromised antenna design and by choosing the power source according to transceiver power requirements, being mindful of the duty cycle / transient window judgment call.
4.7 Architectural Summary

4.7.1 Implementation Review
The architectures discussed include the Blind Transmit tag, the Pulsed Trigger tag, the Single Channel Sharing Hybrid (including the Piloted Triggering variation) and the SCSH/NI system.

The Blind Transmit tag is a transmitter only, periodically broadcasting ID and a mortality indication. Implementation simplicity is an asset. Liabilities include no telemetry data, fixed operation and sparse reporting.

The Pulsed Trigger tag communicates ID via the timing of a high-power pulse synchronized by the reception of a high-power triggering pulse. This approach is better suited to free-space ultra wideband signaling, as antenna and detector tuning is complicated by the pulse signaling used. The ranged operation of an implant requires very powerful pulses with questionable health implications. The semi-active receiver attempts to mitigate the rather extreme interrogator transmit power requirements. Reducing those requirements and making the system scalable results in the use of an active receiver responding to addressed polls.

The Single Channel Sharing Hybrid duty-cycles a receiver to detect the carrier of an interrogator transmission. Receiver “on” times are reduced by eliminating the interrogator turn-around times required when using a single transceiver. The Piloted Trigger provides a constant carrier on a separate channel so that tag receiver “on” times do not have to span interrogator receiver “on” times. The SCSH offers telemetry data and behavioural modifications. The SCSH MAC uses broadcast polling to trigger random-access contention with a TDMA Implied Polling back-off algorithm. A Demand Polling mode allows for tighter control and fixed period single-transmit poll responses.

The SCSH / Networked Interrogators (SCSH/NI) architecture relieves propagation issues and interrogator expense with the use of multiple small interrogators positioned throughout the locale of interest. Each interrogator uses the SCSH MAC to communicate with tags and uses NI MAC to communicate with other interrogators. The NI layer is a self-organizing network. The interrogators are intended to be small (not tiny).
and to function in a fashion similar to wireless sensor networks, without the same resource constraints.

4.7.1 Required Sensors
A common requirement for all architectures is the provision of two sensor types: pressure and temperature. At a minimum the temperature sensor is required to indicate animal mortality. The pressure sensor plays an increasingly important role as the animal ages and spends more of its time foraging at depth. During dives, the tag will save power by suspending transmissions (for the Blind Transmit tag) or Listening (for all others). We anticipate that collecting both temperature and pressure samples will allow for the reasonable assumption that the animal is at sea, further improving tag performance when it is ashore. Gathering this data and modifying tag behaviour is not possible with the Blind Transmit Tag.

4.7.2 Range and Antenna Tuning
A narrow-band antenna likely requires a tuning mechanism as the electromagnetic properties of the animal’s flesh will change with time. Diet strongly affects these properties; antenna drift due to dietary extremes may defeat a system without a tuning mechanism should antenna resonance drift out of band. As the tag is intended to assist in determining sources of animal mortality, failure resulting from dietary extremes is unacceptable.

For a given set of radio link characteristics (including antenna performance), an increased range requires increased power levels. COTS transceivers generally limit available power to regulatory restrictions. These restrictions apply to both interrogator and tag, so without attaining regulatory exemption the range may be increased by adding amplifiers in both the transmit and receive chain of the tag, as well as an antenna switch. The advantage of a Blind Transmit tag is that it may use a power amplifier without requiring an antenna switch.

The problem with power amplifiers in either case is that no antenna tuning mechanism exists. Some COTS transceivers have antenna tuning circuitry, making them an attractive (but low power) choice for animal testing. While an amplified tag would
initially provide longer range it would fail in the long term without an antenna tuning mechanism. Should an antenna tuning mechanism be implemented after the power amplifier (after the switch for transceivers), both Blind Transmit and transceiver-based tags would achieve a similar transmission range. The behavioural modifications and data telemetry available to transceiver-based tags result in a utilitarian wildlife telemetry implant, rather than a simple wildlife tracking implant.

The preferred solution is an application-specific integrated circuit capable of high transmit power levels that performs antenna matching and has a sensitive receiver.

4.8 Conclusion

The use of a SCSH MAC protocol can closely match the system performance of a Piloted Trigger when both tag and interrogator are able to quickly detect channel traffic and when the interrogator avoids the “dead air” resulting from single transceiver turn-around times.

Although Piloted Trigger may be of use for specific antenna-tuning approaches, an on-tag mechanism is more appropriate. While Piloted Trigger requires a fixed frequency architecture, SCSH allows the co-existence of several in-band, independent systems as it is implemented on a per-channel basis.

The Blind Trigger approach has the PHY layer advantage of easy implementation of power amplification, whereas the half-duplex COTS transceivers face costly (in terms of real estate and power consumption) circuitry additions to provide both power amplification and a clean receive path. This “advantage” is an illusion in the face of antenna de-tuning. The Blind Trigger is disadvantaged in its lack of functionality and flexibility as compared to half-duplex tags and is not amenable to aerial surveys.

The ideal tag transceiver would have the following attributes:

- Fast traffic detection capability
- Excellent sensitivity
- High data rate
- High power (3 W+) transmission capability
- Antenna matching circuitry
- Fast spin-up and turn-around times
- Able to synchronize transmissions with channel traffic cessation

Other attributes of the tag should include:

- Low power hibernation with timer
- Fast sensor sampling and storage
- On-demand subsystem power consumption

The interrogator should be more capable than a tag, including

- Zero turn-around times
- Uplink capability
- Behaviour changes according to conditions and user commands

The SCSH MAC protocol combines random-access (contention based), implied polling (TDMA based) and demand polling (Polling TDMA) protocols. Low system traffic and indifference to latency in a star network allow the tags to operate in a highly power-efficient manner.

The SCSH/NI architecture allows the SCSH protocol to proceed with short-range tags and/or in a severely fading environment or one with a complex geography. It can reduce total equipment and installation costs, as well as provide a workable solution for worst-case communications range.
Chapter 5 Implementation

The capabilities of the electronic devices chosen to implement one of the MAC protocols described in Chapter 4 can both introduce difficulties in meeting the specification and allow for specification improvements. For example, a transceiver with received signal strength indication (RSSI) and programmable power levels would provide power-saving opportunities for tags close to an interrogator. Conversely, transceivers may require RF shut-down for payload programming, severely impacting response times and power requirements due to reference crystal spin-up delays.

This appendix will discuss early prototype implementation and specify design for the next generation.

5.1 Single Channel Sharing Hybrid (SCSH)

A single channel sharing scheme was implemented. Hardware designs were varied to provide testing platforms for protocol development, antenna characterization, power management schemes and peripheral interfacing.

Texas Instruments MSP430 microcontroller units (MCU) were used. Designs without peripherals were implemented using the MSP430F1121A to take advantage of the small package size available due to the limited number of port pins. The MSP430F149 was used in designs requiring more control lines. The MSP430 line is specifically designed for low-power battery operated devices and as such provides several power-saving clock modes and the ability to activate and deactivate on-board peripherals according to usage. Port edge transition interrupts are available while the device is in low-power modes, allowing for the exploitation of transceiver logic signals or other peripheral signals to wake the MCU in an event-driven fashion.

The transceiver used was the Nordic nRF905, which is capable of operation in the North American 915 MHz ISM band and the European 868 MHz and 433 MHz ISM bands. The modulation used is Gaussian frequency shift keying (GFSK) with Manchester encoding. Capable of 10 dBm transmissions consuming 30 mA @ 3 V and −100 dBm...
receiver sensitivity consuming 12.5 mA @ 3 V, the nRF905 also provides logic signals indicating carrier detected (CD), address matched (AM) and data ready (DR) conditions.

Unfortunately, while the data payload may be clocked out on the SPI interface while the receiver is active, the radio must be shut down in order to reprogram the destination address or data payload for a transmitted packet. Powering-up the radio incurs a 3ms delay, intended to allow the crystal reference time to stabilize, after which a 650 μs delay is incurred in transitioning from standby mode (STBY) until actual transmission begins. The turn-around times of 550 μs is constrained by PLL response time. Timing information for switching nRF905 modes is shown in Table 5.1.

<table>
<thead>
<tr>
<th>NRF905 Mode Change</th>
<th>Maximum time</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWR_DN to STBY</td>
<td>3 ms</td>
</tr>
<tr>
<td>STBY to RX</td>
<td>650 μs</td>
</tr>
<tr>
<td>STBY to TX</td>
<td>650 μs</td>
</tr>
<tr>
<td>TX to RX</td>
<td>550 μs</td>
</tr>
<tr>
<td>RX to TX</td>
<td>550 μs</td>
</tr>
</tbody>
</table>

Table 5.1 nRF905 Mode Switch Timing

Configuration reprogramming (including data payloads, RF configuration such as power levels, addressing, frequency channels, etc.) requires the radio to be in PWR_DN mode. This is a significant disadvantage in implementing the SCSH protocol as specified.

5.1.1 Base Performance Metric $T_{LI}$

The crucial parameter for system performance is the power consumed during a Listen event $P_L$, where $P_L = P_{avg}T_L$. As the nRF905 was also used to implement interrogator functionality, $T_L$ is established by transceiver turn-around times, $T_{CD}$ and $T_{FS}$.

An FS packet is comprised of a 10-bit preamble, destination address bytes, data payload and CRC. Another disadvantage of the nRF905 is that packets without the proper address are flushed; this means that the demand polling (DP) operation is accomplished
by assigning all tags the same (i.e., broadcast) address and to embed the tag’s “real” address in the data payload. On the other hand, this requirement for identical tag addresses (not tag IDs) permits the use of a single-byte broadcast address, which allows us to shrink the size of an FS packet and thereby reduce $P_L$ via reducing $T_{FS}$ (which reduces $T_L$).

The minimum data payload is a single byte. This will be used as a system status byte, SYS. The CRC is appended automatically by the nRF905 and may be one or two bytes in length.

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Broadcast Address</th>
<th>Data Payload SYS</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 bits</td>
<td>8 bits</td>
<td>8 bits</td>
<td>8 bits</td>
</tr>
</tbody>
</table>

Table 5.2 Minimum FS Packet

The transceiver data rate is 100 kbps, Manchester-encoded. Manchester encoding encodes binary data by level-shifting; a “0” is represented as 01 while a “1” is represented as 10. This approach guarantees that the DC level of any data stream will be zero. The “raw” data transfer rate is then closer to 50 kbps, although the actual rate assumes a Gaussian distribution. Using 50 kbps, $T_{FS}$ is given by:

$$T_{FS} = \frac{34 \text{ bits}}{50 \text{ kbps}} = 680 \mu\text{s}$$

The CD function of the nRF905 appears to require 200 $\mu$s, establishing $T_S = 240\mu$s. $T_L$ and $P_L$ may now be determined as:

$$T_L = 2(T_{FS} + T_{TA}) + T_S = 2.7 \text{ ms}$$

$$P_L = 3 \text{ V} \times 12.5 \text{ mA} \times 2.7 \text{ ms} = 101.25 \mu\text{Ws}$$

This power cost is not representative of the entire Listen event, however. The MCU must awaken to begin the pre-charge and again to start the up radio. We will ignore the MCU power costs for the moment but make the following assumptions:
- boost converter efficiency is 80%
- boot voltage is 15V, so eta cap bank = 1-(3/15)^2 = 96%
- loss due to transceiver capacitance is negligible
- Spin-up costs of 3 ms * 12.5 μA = 37.5 nWs are negligible wrt P_L

\[ P_L = \frac{101.25}{0.96 \times 0.8} = 131.84 \mu Ws \]

A worst-case first pass at assessing system performance may be done by assuming that hibernation mode is never entered. Hibernation would normally occur when a tag transmits an ID (15 min hibernation) or when sensor sampling indicates the animal is at sea (between 4% and 50% as the animal matures). Allocating 50 mAh of a 3V battery pack (i.e., 50 * 3 * 3600 = 540 Ws) allows us to determine the Listen interval T_L by:

\[ T_{LI} = \frac{3600 \times 24 \times 365 \times 3 \times 2.76 ms}{4 h \times 3600} = 6570 T_L = 17.74 s \]

\[ T_{LI} = \frac{3600 \times 24 \times 365 \times 3 \times 0.00013184}{540} = 23.1 s \]

One attraction of the Piloted Trigger is the reduction of T_L to 240 μs (perhaps allowing battery pulse operation) with:

\[ P_L = \frac{3 \times 12.5 \times 240 \times 240 \times 37.5 \times 10^{-9}}{0.8 \times 0.96} = 11.77 \mu Ws \]

\[ T_{LI} = 2.06 s \]

This result indicates the applicability of Piloted Triggering for aerial survey capability.
5.2 SCSH PHY Layer

A prototype built according to the schematic shown in Figure 5.2.1 was used to assess switched capacitor bank design and performance. The battery pack consisted of two CR2016 batteries in series, providing $V_B \approx 6$ V and 190 mAh capacity. An LDO regulator (Micrel 5231) with 0.65 μA quiescent current supplied the MCU. When run from a 3 V supply, the MCU consumes 1.6 μA while sustaining timer crystal operation.

Quiescent timer operation consumes 59.13 mAh over 3 years.

The capacitor bank switch is a Micrel 94053, which is a P-Channel MOSFET with an internal gate pull-up resistor. The device will operate at $V_{GS} = -1.8$ V so the MCU port must be high impedance (not $V_{MCU}$ output) to keep it off and actively pull $V_G$ low to charge the capacitor bank. This is a marginal component choice as the absolute maximum
rating for $V_{GS}$ and $V_{DS}$ is -6 V. The next iterations prototypes will use $V_B = 3$ V and a boost converter for better efficiency.

With this testbed, the capacitor bank voltage $V_{CB} = 6$ V, suggesting a best case efficiency of

$$\eta_{CB} = 1 - \frac{V_E}{V_T^2} = 1 - \frac{3^2}{6^2} = 75\%$$

However, the typical self-discharge of a single 47 μF capacitor is ≈ 0.02CV or 3μA. The charge remaining on the capacitor following a transceiver event is $Q = CV = 141$ μC. Taking $T_{L1} = 23.1$ s and the first approximation of constant self-discharge, less than 50% of the stored charge will seep away from the capacitor bank before the next charging event. An improved estimate of single capacitor bank efficiency is

$$\eta_{CB} = 1 - \frac{V_E^2}{V_T^2} = 1 - \frac{1.5^2}{6^2} = 93.75\%$$

This estimate has implications for pre-charge duration, which will differ according to historic behaviour such as routine Listening or Hibernation.

The Micrel 5233 regulator supplies the transceiver. Ground current varies according to load current and may be estimated from the data sheets for the different transceiver loads.
5.2.1 Sensor Payload

The use of an MSP430F149 adds a hardware UART, hardware SPI capability and a multi-channel ADC. An extraordinary linear temperature sensor, the aSM121 was included as was off-board storage in the form of ferroelectric non-volatile memory (FRAM). While the FRAM accommodated reads and writes at top MCU speed, an oversight in ADC operation frustrated sensor sampling. The ADC port may convert a channel or source an output, but not both – which was tried here.

A small pressure sensor is an important peripheral that could almost double system performance, but was not specified for these prototypes. Performance boosts result from the power savings of entering Hibernation mode while foraging at depth.

Data transfer was tested by supplying a data stream from the interrogator, storing it in FRAM and later reading FRAM and transmitting the data to the interrogator.
5.2.1.1 Interrogator

An interrogator was created via manual modification of the Sensor Payload layout. Additions made included a second antenna, which supplied a Linear Devices LT5534 RF Power Detector. The power detector was used to monitor both interrogator and tag RF traffic as well as to provide a qualitative assessment of the radiation patterns for various antenna types.

Extended firmware functionality was required to sustain communications with a personal computer, as was custom software for the PC terminal.

![Image](image.png)

Figure 5.2.3 Received Data Stream from Tag
5.3 SCSH MAC Protocol Specification

As the MAC protocol is perforce closely tied to hardware capabilities, a generic MAC protocol is presented with notes made as to what adaptations the nRF905 transceiver demanded.

5.3.1 Interrogator MAC

The interrogator must be able to sense traffic in the channel.

The modes available to the interrogator are Demand Polling (DP), Free Scan (FS) solicitation, CMD operations and Tag Data Transfer.

5.3.1.1 Demand Polling

<table>
<thead>
<tr>
<th>Pre-amble</th>
<th>Mask</th>
<th>LAddress</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>b1xxx</td>
<td>8 bits</td>
<td>8 bits</td>
</tr>
</tbody>
</table>

Table 5.3 DP Packet

A DP packet is comprised of pre-amble, Mask byte, address byte and CRC byte. The most significant bit of the mask byte indicates DP operation.

The interrogator alternates DP packets with fixed monitoring intervals. The LAddress byte cycles from 0xFF to 0x00 in descending sequence, allowing tags to predict when their number might be called.

The Mask byte indicates DP operation by setting bit 7. The remaining 7 bits of the Mask byte, along with the LAddress byte, hold the current tag address being polled. Providing masked bits allows for the non-sequential assignment of tag IDs while maintaining fast scans through the available tag population.
5.3.1.2 Free Scan

A Free Scan transmission (FS) alternates with scanning intervals. Minimum FS duration must satisfy the time required by a tag to successfully sense the channel. Scanning interval duration must suffice such that an incoming tag transmission may be sensed by the interrogator.

FS composition depends directly on hardware capabilities with the preferred forms given in order of descending preference:

10101010 ... (or transceiver preamble). Minimum duration must preclude a tag from interpreting another tag’s transmissions as an FS packet.

Preamble : Broadcast Address 0x7F
Preamble : Broadcast Address 0x7FFF
Preamble : Broadcast Address 0x7FFF : CRC

The CRC of the last case would not change and effectively becomes the second byte of a broadcast address.

Note: The nRF905 FS packet required a data byte to be included in the last case.

Upon sensing response traffic, the scanning interval is extended until the packet is received or a fault detected. If a fault is detected, all transmissions are suspended to trigger an Implicit Poll response for contention-free re-transmission from tags which have collided or whose packet failed. When the IP delay has expired, any received packets are examined for data transfer requests. A CMD notifies a selected tag to enter Tag Data
Transfer (TDT) mode; the remaining tags hibernate for 5 minutes plus 0.01 s times their ID number.

A clean packet is examined for a data available flag; a CMD packet is composed and sent. If permission for transfer is granted, the interrogator enters TDT mode.
### 5.3.1.3 CMD Operations

<table>
<thead>
<tr>
<th>Tag Data Transfer CMDs</th>
<th>Mnemonic</th>
<th>Encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Report data availability (M:N)</td>
<td>TDT_RDA</td>
<td>0xDA</td>
</tr>
<tr>
<td>Report Current Temperature</td>
<td>TDT_RCT</td>
<td>0xD5</td>
</tr>
<tr>
<td>Report error conditions</td>
<td>TDT_REC</td>
<td>0xEE</td>
</tr>
<tr>
<td>Report power status</td>
<td>TDT_RPS</td>
<td>0xE7</td>
</tr>
<tr>
<td>Erase sensor M data</td>
<td>TDT_CLR</td>
<td>0x0(M)</td>
</tr>
<tr>
<td>Signal for extended CMDs</td>
<td>TDT_XCMD</td>
<td>0x4A</td>
</tr>
<tr>
<td>Report system time</td>
<td>TDT_RTM</td>
<td>0xD0</td>
</tr>
</tbody>
</table>

#### Mode Control

<table>
<thead>
<tr>
<th>Function</th>
<th>Mnemonic</th>
<th>Encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continue Report</td>
<td>TDT_CTX</td>
<td>0xDD</td>
</tr>
<tr>
<td>Hibernate Default</td>
<td>TDT_SLP</td>
<td>0x2A</td>
</tr>
<tr>
<td>Enter IDO mode</td>
<td>TDT_IDO</td>
<td>0x25</td>
</tr>
<tr>
<td>Enter IP Operation</td>
<td>TDT_IP</td>
<td>0x2F</td>
</tr>
</tbody>
</table>

#### Extended Operand TDT CMDs

<table>
<thead>
<tr>
<th>Function</th>
<th>Mnemonic</th>
<th>Encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Report N latest blocks from sensor M</td>
<td>XT_RMN</td>
<td>0xA(M) NN</td>
</tr>
<tr>
<td>Report blocks B to Y from sensor M</td>
<td>XT_RM BY</td>
<td>0xB(M) BB YY</td>
</tr>
</tbody>
</table>

#### System CMDs

<table>
<thead>
<tr>
<th>Function</th>
<th>Mnemonic</th>
<th>Encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Set System Time Day/Hour/Minutes</td>
<td>CMD_SST</td>
<td>0x33 (6 bytes)</td>
</tr>
<tr>
<td>Set Clock Adjustment Coefficient</td>
<td>CMD_SCC</td>
<td>0x3C (3 bytes)</td>
</tr>
<tr>
<td>Set $T_{LI}$ to M for N Intervals</td>
<td>CMD_IMN</td>
<td>0x6(M) NN</td>
</tr>
<tr>
<td>Hibernate From X to Y (X,Y are times)</td>
<td>CMD_HXY</td>
<td>0x77 (12 bytes) or 0x78 (6 bytes)</td>
</tr>
<tr>
<td>Set sensor M sample interval to N</td>
<td>CMD_SMN</td>
<td>0x8(M) NN NN</td>
</tr>
</tbody>
</table>

Table 5.4 CMD Operations
CMD operations allow for the manipulation of tag behaviour. Typically, the first CMD to tag requesting data transfer is the Report data availability (M:N). The tag responds in a format where M is the sensor ID and N is the number of blocks of data available. After a CMD packet, all interrogator transmissions are suspended pending tag communications or a time-out.

Tag data transfer CMDs are accomplished with a single byte, excepting the data block requests. These requests occur only while the tag is operating in TDT mode wherein maximum power is available to the tag for communications.

System CMDs occur only while the tag is in TDT mode.

5.3.1.4 Tag Data Transfer MAC
Both interrogator and tag enter the Tag Data Transfer mode upon issuance of a CMD requiring data transfer in either direction. Interrogator transmissions are immediately suspended.

To issue System CMDs and Extended Operand TDT CMDs the interrogator must first issue TDT_XCMD, which requires the tag to prompt the interrogator for the CMD once pre-charge is complete.
Tag transfers involve the tag charging sufficiently for the transmission size and a reply reception, transmitting the data and receiving further control messages. The channel is reserved until communications are completed.

### 5.3.1.5 Listen

The tag will be equipped with the ability to detect the presence of traffic in the channel. A tag will periodically (at intervals of $T_{L}$) attempt to detect an interrogator broadcast packet (Listen).

Listen duration ($T_{L}$) will be a minimum of 1.2 times the interval during which the interrogator is not transmitting.

Sufficient power must be available to extend Listen to encompass two complete interrogator Free Scan packets and the interval between them ($T_{LX}$).

Upon detection of traffic the tag will monitor the channel until the extended Listen duration has expired or an FS packet has been received.

Should an FS packet be received, the tag will enter ID Response mode. Should the interval expire with two or less channel traffic transitions, the tag will interpret this as an OD operation and will enter OD Response mode. In all other cases the tag will remain in IDO operation and sleep until $T_{L}$ has again elapsed.
5.3.1.6 ID Response for nRF905

The tag will behave according to the SYS status byte received in the FS packet. SYS encoding and tag response are shown in Table 5.5.

<table>
<thead>
<tr>
<th>SYS Status : Code</th>
<th>Tag Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Solicitation : b0101 0101 0x55</td>
<td>Begin pre-charge for ID transmission and CMD reception. Prepare ID packet.</td>
</tr>
<tr>
<td>IP Request : b1111 0000 0xF0</td>
<td>Implicit Poll : pre-charge ID and synchronize transmission to FS end.</td>
</tr>
<tr>
<td>IDO Request : b1100 1100 0xCC</td>
<td>IDO : pre-charge for ID only. Transmit without CMD reception or hibernation.</td>
</tr>
<tr>
<td>DP Counter : b1001 nnnn 0x9N</td>
<td>Demand Polling will commence after nnnn FS intervals. Pre-charge to monitor DP Packet to establish countdown.</td>
</tr>
<tr>
<td>Receive Request : b0110 nnnn 0x6N</td>
<td>Transmit ID and prepare for extended reception after nnnn FS intervals.</td>
</tr>
</tbody>
</table>

Table 5.5 nRF905 SYS Byte

5.3.1.7 Preferred Tag Packet Formats

All interrogators share a common address 0xF0. Tag ID packets for an FS reply take the form

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Int. Address</th>
<th>Tag ID</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0xF0</td>
<td>2 bytes</td>
<td>1 byte</td>
</tr>
</tbody>
</table>

Table 5.6 FS ID Reply

ID replies for IP operation or DP operation, along with TDT send prompts, are simply:
Table 5.7 IP, DP and TDT Send Packet

TDT ACK / Send packets are:

<table>
<thead>
<tr>
<th>Preamble</th>
<th>OxFO</th>
<th>OxFO</th>
</tr>
</thead>
</table>

Table 5.8 ACK / Send Packet

Data transfer packets are:

<table>
<thead>
<tr>
<th>Preamble</th>
<th>0xF0</th>
<th>Transfer ID</th>
<th>Byte Count</th>
<th>Data Bytes</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1 byte</td>
<td>1 byte</td>
<td>N bytes</td>
<td>2bytes</td>
</tr>
</tbody>
</table>

Table 5.9 Data Transfer Packet

The Transfer ID identifies the remaining Data Transfer blocks, inclusive. For a data transfer requiring three transmissions, the Transfer ID proceeds 3, 2, 1.
Chapter 6 Prototype Data

Early system development focused on the use of patch antennas for the tag. Initial size specifications for the tag allowed the 2.4 GHz ISM band to be utilized, as an inset-feed patch antenna could be made to fit within the allowable footprint.

Electronics development abruptly switched to the 5.8 GHz ISM band when the size specification for the tag was reduced to half the previous footprint. At the time, the dramatic effects of a variable superstrate on patch antenna tuning and resonance was unknown. Increasing the frequency of operation increases losses in the tissue layer while allowing for an electrically efficient antenna; lowering the frequency of operation reduces tissue loss while increasing antenna losses.

Unfortunately, a link budget that weighed antenna efficiency, tissue losses and signal propagation was not sufficiently analyzed at the time. Subsequent evaluation led to operation in the 915 MHz ISM band and the use of loop antennas.

6.1 Circuitry at 5.8 GHz

The signaling scheme intended for implementation at 5.8 GHz was for tags to detect an interrogator synchronization pulse train and reply with a single, high-power pulse in the appropriate timeslot as shown in Figure 6.1.

![Figure 6.1 Synchronous Tag Reporting](image)
Tag functionality therefore required both the ability to detect interrogator pulses and the ability to respond with timed pulses. Prototype circuitry was produced for testing receive and transmit paths independently as well as for combining both paths on a single device.

Figure 6.2 shows a schematic and physical prototype for the receive path. The antenna feeds an unassisted power detector. A fourth-order Sallen-Key filter limits the response bandwidth to pass the interrogator pulse envelope (10 μs pulse width) while reducing false detections. An operational amplifier conditions the filter output to levels that trigger an edge interrupt at the microcontroller.
Figure 6.3 features the addition of a low-noise amplifier to the receive path in order to increase the effective range of interrogator detection.

![Figure 6.3 Power Detector With Low-Noise Amplifier](image)

The schematic of Figure 6.4 shows the transmit path. The microcontroller programs a digital to analog converter (DAC) which controls a free-wheeling voltage controlled oscillator (VCO). The VCO output is amplified by a gain block and a power amplifier. The use of a phase-locked loop (PLL) is problematic due to the limited real estate available on the tag; it is also unnecessary as the system needs only to deliver pulsed power in the detector bandwidth of the interrogator. A certain noise floor of the interrogator detector must be accepted in order to accommodate the frequency “slop” resulting from the use of a free-wheeling VCO in the tag.
Figure 6.4 Microwave Pulse Generator
Figure 6.5 shows a complete tag combining both transmit and receive paths.

Figure 6.5 Complete Microwave Transceiver
6.2 Circuitry at 915 MHz Circuitry

Once it was determined that 5.8 GHz was an inappropriate frequency of operation, designs for operation at 915 MHz were created. The smallest footprint for implementing both a transmit and receive path at 915 MHz was obtained through the use of a commodity transceiver, such as the Nordic nRF905 or Integration Associates IA4420. Prototypes implemented using the nRF905 are shown in the following sections.

6.2.1 Programmer

An RS-232 programmer for Texas Instruments' MSP430 series of microcontrollers was fabricated based on the design presented in Application Report SLAA096B from Texas Instruments (TI). The programmer hardware is shown in Figure 6.6.
6.2.2 MSP430F149 Designs

The design presented in section 5.2.1 was physically implemented as shown in Figure 6.7. This device was used as a firmware development platform for external memory communications and was intended to test the performance of the asM121 temperature sensor. Misuse of the ADC peripheral resulted in the asM121 test failing, with the benefit of proper use of the ADC being ascertained.

Transceiver operation for this device was tested and found to be operational. A range test using a quarter-wave whip antenna (without tweaking the matching network) showed communication at 800 meters with a battery supply.

Figure 6.7 Sensor Payload Device

Another device based on the section 2.5.1 design was the “interrogator” shown in Figure 6.8. It is essentially the same design as that shown in Figure 6.7 with the addition of a second antenna feeding a power detector, a different MCU package type and some power supply changes. It was intended that the detector would be sampled by the ADC.
but again, faulty utilization led to the detector being monitored strictly by an oscilloscope.

![Image of an interrogator device](image)

**Figure 6.8 Interrogator Device**

### 6.2.3 MSP430F1121A Designs

A significantly smaller footprint was obtained using TI’s MSP430F1121A (‘1121A). Although available functionality is much reduced, there are sufficient available ports for control of the transceiver and power switching. External peripherals such as the FRAM and the asM121 are not used.

The design shown in Figure 6.9 was used to develop protocol firmware for the MSP430F1121A. The design accommodates both battery and external power supplies.
This basic layout was also intended to be used for testing several antenna types. These included a small (9.5 x 9.5 mm) loop antenna (Figure 6.10), a 24 x 25 mm loop antenna (Figure 6.11) and a shorted half-patch inset feed antenna (Figure 6.12). All layouts functioned at worktable separation distances; only the 9.5 x 9.5 mm loop device was range-tested. With the small loop oriented vertically, an in-plane range of 350 meters was obtained. Subsequent testing with the interrogator's detector showed that peak power was not obtained in-plane, but rather at about a 45 degree angle out-of-plane. This result is surprising and may be related to the proximity at which the peak power testing occurred. Unfortunately, a further range test was not conducted.
Figure 6.10 9.5 x 9.5 mm Loop Antenna

Figure 6.11 24 x 25 mm Loop Antenna
6.3 Scope Traces

Most oscilloscope trace captures were used for firmware development with very few taken to demonstrate circuit operation. Nevertheless, some of these captures are presented here.

An interesting one is shown in Figure 6.13. Voltage across a sensing resistor was used to monitor current consumption during the operation of the design shown in Figure 6.9. The firmware appeared to work fine, but the full range of required functionality was not being utilized. Certain timing issues of payload examination and operational turn-around didn’t get a workout until later on, whereupon remaining bugs were quashed. So although the timing in the diagram isn’t accurate, the current consumption levels are indicative of normal operation.
Figure 6.13 Current Monitoring

Figure 6.14 shows detected power levels for periodic interrogator transmission with a tag “waking” periodically to listen for the interrogator signal and then responding. The tag reliably detects the interrogator signals (the tallest pulses) and responds (the shorter pulses).

Figure 6.14 Interrogator / Tag Communication
Figure 6.15 shows another view of the same operation, with the second oscilloscope trace connected to the tag transmit enable logic level.

Figure 6.15 Communication Detail

Figure 6.16 shows capacitor bank voltage drop with an undersized capacitor bank. Doubling the capacitance of the bank resulted in a voltage drop within acceptable levels for transceiver operation. The capacitor bank voltage drop is shown for unrestricted current draw from the battery in Figure 6.17 and for limited current draw from the battery in Figure 6.18.
Figure 6.16 Capacitor Bank Voltage Drop

Figure 6.17 Capacitor Bank Voltage With Unlimited Battery Draw
Figure 6.18 Capacitor Bank Voltage With Limited Battery Draw
Figure 6.19 shows the battery terminal voltage during a tag listen / transmit event. Unfortunately insufficient documentation exists to determine if this event is with a limited or an unlimited current draw from the battery. Notice that the impedance seen at the transceiver increases during transmission.

![Figure 6.19 Battery Terminal Voltage](image)

Some miscellaneous traces of interest remain. Figure 6.20 shows a low resolution trace of transceiver current consumption during Listen and Listen / Transmit events. Figure 6.21 is a troubleshooting trace localizing voltage regulator stability problems due to an undersized output capacitance.
Figure 6.20 Low Resolution Listen / Transmit Events

Figure 6.21 Regulator Instability
Chapter 7 Concluding Remarks and Further Work

The next iteration of prototypes involves several compromises in function and approach. Most significantly, the battery payload has been changed from Lithium coin cells to Silver Oxide cells. Two major design approaches remain: a short-range version which directly utilizes the IA4420 transceiver and a long-range version which utilizes a GSM amplifier (RFMicro Device’s RF2173) and supercapacitor (the Cap-XX GW209).

7.1 Battery Consequences

Silver Oxide batteries maintain a terminal voltage of 1.55 V essentially to their end-of-life. The use of DC/DC conversion schemes with these batteries represents unnecessary loss due to conversion inefficiencies. Therefore circuitry is supplied directly from a battery buffered by a capacitance.

The zinc anode used in silver oxide batteries represents a gassing hazard. This hazard is mitigated by the ceramic housing for the tag, which is built to withstand pressure in excess of 30 atmospheres.

The arrangement of battery payload, supercapacitor and PCB is shown in Figure 7.1. A detail of the battery connection is shown in Figure 7.2.

Figure 7.1 Tag Payload Arrangement
7.2 Major Design Approaches

An approximate layout of the complete tag is shown in Figure 7.3. The copper representing the antenna will actually form a loop for the double-ended output of the short-range tag. The single-ended output of the long-range tag requires further antenna design to include a tuning mechanism.
A PCB layout for a short-range tag is shown in Figure 7.4.

Figure 7.4 Short-Range Tag Utilizing IA4420

The layout shown in Figure 7.5 retains an old battery payload. Current design utilized the several smaller batteries similar to that shown in Figure 7.4.
7.3 Conclusion

The critical constraint for this project is the volume available for the tag; the restricted volume negatively impacts the available energy, electronics payload and antenna size. When considering volume the ideal implementation involves reducing the electronics payload to a minimum with custom designed integrated circuitry, reducing battery volume and increasing available energy with the use of renewable energy sources such as might be obtained through energy scavenging and increasing the volume available to the antenna in order to improve efficiency.

7.3.1 Electronics

Reducing the electronics volume using COTS products is accomplished by accepting the low power transmissions resulting from the use of commercial ISM band transceivers. The volume thereby made available may be used to increase the battery payload and/or increase antenna dimensions, or possibly for the inclusion of an energy scavenging
mechanism. The necessarily short-range communications of the tag could yet suffice for comprehensive sea lion identification at a haul-out when the system architecture includes a multiplicity of interrogators located about the haul-out.

Provision of sufficient energy for radio operations of the tag requires one of three basic approaches: directly driving the electronics from the batteries, periodic accumulation of energy on a capacitor bank or directly buffering the batteries with a large capacitance.

The batteries are incapable of directly driving loads on the order of two or three amperes; the lighter loads of short-range tags also exceed the batteries optimal sourcing current rating but the reduction in effective energy capacity may be acceptable when the frequency of use and available capacity are such that longevity goals are satisfied.

Power conversion techniques are needed when the battery payload terminal voltage is inappropriate for the electronics and when periodic capacitive bank charging is utilized. Lithium cells typically require regulation and as their terminal voltages droop would require up-conversion to extend their useful life. Periodic capacitive banks require up-conversion from terminal voltages (to increase efficiency and available energy) and regulation to feed the electronics. Conversion and regulation have efficiencies of roughly between 70% - 90%. Multiple conversions can easily “waste” one-third to one-half of the energy capacity of the batteries.

The use of super-capacitors to buffer batteries that have acceptable terminal voltage characteristics (e.g. silver oxide cells) eliminates the need for power conversion. This comes at the cost of energy wasted through the self-discharge of the super-capacitor and the tag volume required to house the capacitor. COTS super-capacitors in general have unacceptably high self-discharge; however, a product with relatively low self-discharge (the cap-XX GW209) that exceeds the required capacitance was located. Roughly one-third of the available tag floor-space is occupied by the GW209 package, strongly suggesting that a custom-built super-capacitor of reduced package volume and reduced capacitance would be better suited to this application.
7.3.2 Antenna

An electrically longer antenna results in both efficiency gains and a higher sensitivity to de-tuning. As some ISM band COTS transceivers (the IA4420 from Integration Associates is an example) include an antenna tuning mechanism, the short-range tags immediately benefit from increased antenna volume. Long-range COTS tags require a power amplifier and therefore a larger, more efficient antenna would also require a tuning mechanism. This is difficult to do using COTS parts as the electronics footprint is increased substantially when using a power amplifier and easy approaches (such as the use of varactors) is made difficult by the high power levels and restricted available volume.

7.3.4 Energy Source

The slim profile of the tag quickly reduces the available battery choices to a handful of coin cells. Of the battery chemistries available, the popular Lithium cells require power conversion mechanisms with their attendant inefficiencies and increased electronics real-estate requirements. Silver oxide cells provide a stable terminal voltage and can be used in series to provide the desired voltage levels (3.0 – 3.3 V) of the active electronics. Silver oxide cells use a zinc terminal, which can result in gassing once the cells are dead. This difficulty is overcome by the robust tag housing, which is able to withstand very high pressure.

Energy scavenging approaches are strongly indicated here; the use of a supercapacitor obviates the need for rechargeable batteries for scavenging mechanisms. Conditioning circuitry would still be necessary.

7.3.5 Ideal Systems

The ideal tag would be comprised as follows:
**Energy Source**

Prismatic silver oxide cells augment an energy scavenging mechanism that charges a super-capacitor. The primary cells may be required early in a pup’s life if vibrational scavenging is used (due to the relative inactivity of the animal) or if pressure conversion (and possibly thermal scavenging) is used, due to the relative paucity of foraging dives early in a pup’s life.

**Electronics**

A custom integrated circuit that encompasses all required functionality renews the possibility of using much shorter duration transmissions. The IC would be able to quickly detect the presence of an interrogator pilot and respond with a very short, high-power transmission. An antenna tuning mechanism would be integrated. Conditioning circuitry for the energy scavenging mechanism would also be integrated.

**Antenna**

The antenna efficiency would be maximized through occupying the largest volume possible.

**7.3.6 Immediate Next Steps**

Vibrational data of Stellar sea lion movement will be gathered wirelessly from a MEMS accelerometer, with an eye to development of an energy scavenging approach.

Prototypes of high- and low-power tags will be fabricated. The devices will be implanted in live pigs for testing. A tuning mechanism for the high-power design is undergoing development.
Bibliography


109. Olawale, K.O., Petrell, R.J., Michelson,D.G., Trites, A.W., *The Dielectric Properties of the Cranial Skin of Five Young Captive Steller Sea Lions (Eumetopias jubatus), and a Similar Number of Young Domestic Pigs (Sus scrofa) and Sheep (Ovis aries) Between 0.1 and 10 GHz*. Physiological Measurement, 2005.


