ACKNOWLEDGEMENTS

The two years that I have spent researching Bluetooth technology has been challenging at times, but ultimately very rewarding. Working for the Center for Wireless Telecommunications was an integral part of what I consider an excellent Master’s education. First of all, Dr. Dennis Sweeney deserves a great deal of thanks for putting up with my constant badgering of questions and for all his advice and suggestions. I don’t know many other advisors who would take that much time out of their day to attend to their graduate students. Secondly, the full extent of this research could not have been achieved without the help of Thomas Rondeau. He possesses a wealth of knowledge on Bluetooth technology, which came in very handy when I ran into problems along the way. Many thanks to him for helping with some of the software coding involved in this thesis, for his suggestions and for assisting me in the measurement process.

So many others have helped me in other ways, for which I am equally grateful. I thank Shelley Johnson for loaning me her microwave oven and the CWT cart to carry around equipment. Also, thanks to everyone else in the CWT who have helped to keep my work personal and sociable.
# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................................................................................iii
LIST OF TABLES ....................................................................................................................vii
LIST OF FIGURES ................................................................................................................viii
LIST OF EQUATIONS ..............................................................................................................xi

## CHAPTER 1: INTRODUCTORY OVERVIEW

1.1 Scope of the thesis ........................................................................................................1
1.2 Relevance of this work ...............................................................................................3
1.3 Outline of the thesis .....................................................................................................4

## CHAPTER 2: BACKGROUND MATERIAL

2.1 Bluetooth Technology Overview ..............................................................................6
2.2 Bluetooth Networking and Operation .......................................................................6
2.3 Frequency Hopping Spread Spectrum (FHSS) .........................................................8
2.4 The Co-Existence Problem .......................................................................................8
2.5 Packet Transmission Overview ................................................................................9
2.6 Microwave Oven Overview ......................................................................................20
2.7 Previous Methods of Characterizing Ovens ...........................................................25
2.8 Interference Literature Survey ................................................................................35

## CHAPTER 3: OVEN SPECTRAL CHARACTERIZATION

3.1 Introduction ................................................................................................................37
3.2 Spectrum Measurement Concept .............................................................................37
3.3 Oven Characterization ..............................................................................................42
3.4 Conclusion ................................................................................................................55
**CHAPTER 4: INTERFERENCE EXPERIMENTAL SETUP**

4.1 Introduction ........................................................................................................57  
4.2 Continuous Wave Interference Experiment Setup ..............................................57  
4.3 Interference Test ...............................................................................................61  
4.4 Data Processing Procedure .............................................................................63  
4.5 Results of the CW Test .....................................................................................67  
4.6 FHSS Selection Program .................................................................................68  

**CHAPTER 5: SINGLE CHANNEL PER PREDICTIONS**

5.1 Introduction ........................................................................................................70  
5.2 Bluetooth Receiver Calibration Concept ..........................................................70  
5.3 Receive Power Measurement Procedure ..........................................................71  
5.4 Receive Power Measurements for Channels 50-54 .........................................72  
5.5 Channel C/I Thresholds and Number of Packet Errors .................................75  
5.6 Theoretical Calculation Results .......................................................................77  

**CHAPTER 6: INTERFERENCE EXPERIMENTS SETUP AND RESULTS**

6.1 Introduction ........................................................................................................80  
6.2 Interference Experiment Setup .........................................................................80  
6.3 Experimental Procedure ..................................................................................82  
6.4 Environmental Scenarios and Results ............................................................82  
6.5 Throughput Analysis .......................................................................................120  

**CONCLUSION** ........................................................................................................122  
**APPENDIX A: Serial Cable Pinout and LabView Program** ................................124  
**APPENDIX B: Matlab spectral plotting function, ovenpwr.m** ............................127  
**APPENDIX C: Matlab FHSS description and code** .............................................128
LIST OF TABLES

Table 2.5.2-1. ACL link packet types .................................................................11
Table 2.5.2-2. ACL packet types ....................................................................15
Table 2.6.3-1. Vertical and horizontal polarization correlation results for measured ovens .................................................................................................................................27
Table 3.3.1. Oven Specifications .......................................................................44
Table 5.4.1. Received powers for channels 50-54 with the slave unit connected ....74
Table 5.6.1. Single-channel calculations ............................................................78
Table 6.4.1. Accuracy of Calculated versus Measured Packet Errors .............92
Table 6.5.1. Throughput results of the Emerson oven experiments ................121
Table 6.5.2. Throughput results of the G.E. oven experiments .........................121
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 2.2.1.</td>
<td>The Bluetooth Stack</td>
<td>7</td>
</tr>
<tr>
<td>Figure 2.3.1.</td>
<td>Bluetooth available bandwidth</td>
<td>8</td>
</tr>
<tr>
<td>Figure 2.5.1.</td>
<td>Standard packet format</td>
<td>10</td>
</tr>
<tr>
<td>Figure 2.5.2-2.</td>
<td>Standard packet format</td>
<td>15</td>
</tr>
<tr>
<td>Figure 2.5.3.</td>
<td>Rate 1/3 FEC bit-repetition encoding scheme</td>
<td>16</td>
</tr>
<tr>
<td>Figure 2.5.4-1.</td>
<td>HEC generation and checking</td>
<td>18</td>
</tr>
<tr>
<td>Figure 2.5.4-2.</td>
<td>CRC generation and checking</td>
<td>18</td>
</tr>
<tr>
<td>Figure 2.6.1-a1.</td>
<td>Zero-span spectrum of a residential microwave oven</td>
<td>22</td>
</tr>
<tr>
<td>Figure 2.6.1-a2.</td>
<td>Max-hold spectrum for a residential microwave oven</td>
<td>22</td>
</tr>
<tr>
<td>Figure 2.6.1-b.</td>
<td>Max-hold plot for a two magnetron commercial microwave oven</td>
<td>23</td>
</tr>
<tr>
<td>Figure 2.6.3-1.</td>
<td>Antenna polarization variation with Oven #4</td>
<td>26</td>
</tr>
<tr>
<td>Figure 2.6.3-2.</td>
<td>Antenna polarization variation with Oven #8</td>
<td>26</td>
</tr>
<tr>
<td>Figure 2.6.3-3.</td>
<td>Measurement antenna oriented in the H-plane</td>
<td>28</td>
</tr>
<tr>
<td>Figure 2.6.3-4.</td>
<td>Measurement antenna rotated 90°</td>
<td>28</td>
</tr>
<tr>
<td>Figure 2.7.3-1.</td>
<td>NTIA measurement of oven Time vs. Amplitude at 2450 MHz</td>
<td>33</td>
</tr>
<tr>
<td>Figure 2.7.4.</td>
<td>Relating Time-and Frequency-Domain measurements to actual signal time-frequency characteristics</td>
<td>34</td>
</tr>
<tr>
<td>Figure 3.2.1.</td>
<td>LabView Data Acquisition Program User Interface</td>
<td>39</td>
</tr>
<tr>
<td>Figure 3.2.2.</td>
<td>Experimental setup for collecting oven emissions and Bluetooth data</td>
<td>41</td>
</tr>
<tr>
<td>Figure 3.3.2-1.</td>
<td>Sharp-Carousel Oven PSD measured over a 63 second interval</td>
<td>46</td>
</tr>
<tr>
<td>Figure 3.3.2-2.</td>
<td>Overhead shot showing the Sharp-Carousel Oven PSD</td>
<td>47</td>
</tr>
<tr>
<td>Figure 3.3.2-3.</td>
<td>General Electric Oven PSD measured over a 60 second interval</td>
<td>48</td>
</tr>
<tr>
<td>Figure 3.3.2-4.</td>
<td>Overhead shot showing the General Electric Oven PSD</td>
<td>49</td>
</tr>
<tr>
<td>Figure 3.3.2-5.</td>
<td>Emerson (MW8126 W/S/D) Oven PSD measured over a 62 second interval</td>
<td>50</td>
</tr>
<tr>
<td>Figure 3.3.2-6.</td>
<td>Overhead shot showing the Emerson (MW8126 W/S/D) Oven PSD</td>
<td>51</td>
</tr>
<tr>
<td>Figure 3.3.2-7.</td>
<td>Emerson (MW8107WA) Oven PSD over a 65 second interval</td>
<td>52</td>
</tr>
<tr>
<td>Figure 3.3.2-8.</td>
<td>Overhead shot showing the Emerson (MW8107WA) Oven PSD</td>
<td>53</td>
</tr>
</tbody>
</table>
Figure 4.2.1. CW Interfering Spectral Point at 2.440 GHz ...........................................59
Figure 4.2.2. CW Experimental Setup .............................................................................60
Figure 4.3.1. Tektronix Protocol Analyzer’s Baseband log file .....................................62
Figure 4.4.1. Bluetooth Handshaking Transmission without interference .....................64
Figure 4.4.2. CW Interference on Bluetooth Handshaking Test ....................................65
Figure 4.4.3. CW Interference on Bluetooth Data Transmission .....................................66
Figure 5.4.1. Bluetooth Receive Power measurement setup ...........................................73
Figure 5.4.2. Slave unit’s transmitted and received signals ............................................75
Figure 6.2. Experimental setup for collecting oven emissions and Bluetooth data ......81
Figure 6.4.1. Oven in the same room with the piconet ................................................84
Figure 6.4.2. DM Packets transmitted over one meter without oven interference ......85
Figure 6.4.3. DH Packets transmitted over one meter without oven interference ......86
Figure 6.4.4. Emerson interfering from the Bluetooth Lab ............................................89
Figure 6.4.5. Emerson affecting DM1 transmission .......................................................90
Figure 6.4.6. Emerson affecting DH1 transmission .......................................................91
Figure 6.4.7. General Electric interfering from the Bluetooth Lab ..................................93
Figure 6.4.8. G.E. oven affecting DM1 transmission ......................................................94
Figure 6.4.9. G.E. oven affecting DH1 transmission ........................................................95
Figure 6.4.10. Oven in the room across the hall with the door open .........................96
Figure 6.4.11. Emerson affecting DM1 transmission from other room ......................98
Figure 6.4.12. Emerson affecting DH1 transmission from other room ....................99
Figure 6.4.13. GE affecting DM1 packets from across the hall ..................................100
Figure 6.4.14. GE affecting DH1 packets from the other room ................................101
Figure 6.4.15. Oven and slave in room across the hall with the door open .............102
Figure 6.4.16. Emerson and slave in room across hall affecting DM transmission ......103
Figure 6.4.17. Emerson affecting DH transmission when oven and slave are in room
across the hall ......................................................................................................................104
Figure 6.4.18. Environmental layout of the CWT’s Graduate Student Lab ...............106
Figure 6.4.19. Oven in the Grad lab affecting DM transmission .................................108
Figure 6.4.20. Oven in Grad Lab affecting DH transmission .......................................109
Figure 6.4.21. Oven behind drywall affecting DM transmission ...............................111
Figure 6.4.22. Oven behind drywall affecting DH transmission ..........................112
Figure 6.4.23. Emerson in stairwell affecting DM transmission ..........................114
Figure 6.4.24. Emerson in stairwell affecting DH transmission ..........................114
Figure 6.4.25. Experimental setup in the outdoor environment ..........................115
Figure 6.4.26. Interference results for a 30 m link distance shows poor performance .116
Figure 6.4.27. Emerson’s effects on DM1 transmission for a 72 m link distance .......118
Figure 6.4.28. Emerson’s effects on DH1 transmission for a 72 m link distance .......119
<table>
<thead>
<tr>
<th>Equation</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation 2.7.1-1</td>
<td>31</td>
</tr>
<tr>
<td>Equation 2.7.1-2</td>
<td>31</td>
</tr>
<tr>
<td>Equation 4.2.1</td>
<td>60</td>
</tr>
<tr>
<td>Equation 4.2.2</td>
<td>60</td>
</tr>
<tr>
<td>Equation 5.2.1</td>
<td>70</td>
</tr>
<tr>
<td>Equation 5.5.1</td>
<td>76</td>
</tr>
<tr>
<td>Equation 5.5.2</td>
<td>76</td>
</tr>
<tr>
<td>Equation 5.5.3</td>
<td>77</td>
</tr>
</tbody>
</table>