ADVANCED EMBEDDED SYSTEMS AND SENSOR NETWORKS FOR ANIMAL ENVIRONMENT MONITORING

DISSertation

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ABSTRACT

Advancements in sensing and monitoring of air quality parameters within confined animal feeding operations have been realized through the application of embedded systems and advanced networking. The development of an embedded vibration sensor to detect the presence of ventilation fan activity provided researchers with an improved method to monitor ventilation from high capacity CAFO facilities. Experiments revealed over estimation errors common to the majority of passive ventilation sensors. Analysis of ventilation sensor systems resulted in proposed limits to overall measurement error by minimizing the modulus of fan on-time and sampling time.

Controller Area Networks were found to be a viable means to link multiple analog and digital sensors through a multi-master based embedded network. It was found that signal attenuation was significant as bus lengths increased to a maximum of 600 meters. This attenuation was counteracted by reducing the baud rate of the communication and allowing for longer bit times. Signal reflection of the individual bits was another major factor of transmission error caused by the mismatch of impedance between the signal wire and the termination resistor.

Wireless sensor networks were also evaluated for their potential to act as the data communication network within a multi-point sampling system inside a CAFO.
Results from experimental path loss studies found many factors including antenna orientation, enclosure thickness, free space, antenna height, animal cages, and concrete floor separations to all be statistically relevant factors in determining the overall system path loss. It was further found that linear separation within an aisle and number of cage separations provided the highest levels of signal attenuation.

A model was developed to predict the path loss at any point within a poultry layer facility based on the aisle and cage separation terms. The model was able to predict 86% of the system variability and was able to produce an average error of -0.7 dB for all combined points. The verification of all theoretical path loss models indicates that when applied to new systems not representative of poultry layer facilities, fundamental laws can be used to create initial predictions for path loss.
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TABLE OF CONTENTS

Abstract .......................................................................................................................................................... ii

Acknowledgements .................................................................................................................................. iv

Vita ............................................................................................................................................................. vii

List of Tables ............................................................................................................................................ xiii

List of Figures ............................................................................................................................................ xv

List of Equations.................................................................................................................................... xxii

Chapters:

1. Introduction ............................................................................................................................................ 1

2. Literature Review ................................................................................................................................. 6
   2.1. Introduction to Air Quality Engineering ..................................................................................... 6
   2.2. Embedded Sensors for Agricultural Systems ............................................................................. 8
       2.2.1. Embedded Sensors ............................................................................................................. 8
       2.2.2. Networked Embedded Sensors ..................................................................................... 10
       2.2.3. Point-To-Point Wireless Embedded Sensors ................................................................ 12
   2.3. Networking of Agricultural Sensors ......................................................................................... 15
       2.3.1. Definition ......................................................................................................................... 15
       2.3.2. Topologies ....................................................................................................................... 17
       2.3.3. Wired Sensor Network Protocols – Controller Area Network .................................. 22
       2.3.4. Wireless Network Protocols ......................................................................................... 23
   2.4. Applications of Wireless Sensor Networks .............................................................................. 26
       2.4.1. Wireless Ethernet ............................................................................................................. 26
       2.4.2. Bluetooth ....................................................................................................................... 27
       2.4.3. Zigbee ............................................................................................................................ 28
       2.4.4. Radio Frequency Identification Devices (RFID) ......................................................... 28
       2.4.5. Cellular .......................................................................................................................... 29
   2.5. Modeling Performance of Wireless Sensors .............................................................................. 30
       2.5.1. Background Fundamentals .............................................................................................. 30
       2.5.2. Previous Research Documentation .................................................................................. 39
   2.6. Gap Analysis ................................................................................................................................. 43
       2.6.1. Ventilation Measurement ............................................................................................... 45
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Ohio animal production statistics. Source: NASS, 2002.</td>
<td>7</td>
</tr>
<tr>
<td>Table 2</td>
<td>Comparison of techniques for measuring airflow from agricultural ventilation fans.</td>
<td>61</td>
</tr>
<tr>
<td>Table 3</td>
<td>Sensor response to fan testing with a disengaged propeller.</td>
<td>73</td>
</tr>
<tr>
<td>Table 4</td>
<td>Vibration sensor output over a range of fan rotational speeds.</td>
<td>77</td>
</tr>
<tr>
<td>Table 5</td>
<td>Sampling errors associated with passive ventilation sensors in a tunnel ventilated poultry layer facility over a 27 day period during March and April of 2007.</td>
<td>117</td>
</tr>
<tr>
<td>Table 6</td>
<td>Data transmission performance for CAN bus system operating at 50 kbits/sec baud rate and various bus lengths.</td>
<td>134</td>
</tr>
<tr>
<td>Table 7</td>
<td>Data transmission performance for CAN bus system operating at 100 kbits/sec baud rate and various bus lengths.</td>
<td>134</td>
</tr>
<tr>
<td>Table 8</td>
<td>Data transmission performance for CAN bus system operating at 250 kbits/sec baud rate and various bus lengths.</td>
<td>135</td>
</tr>
<tr>
<td>Table 9</td>
<td>Summary of sensor networking capacity for a CAN bus system operating at a 70% bus load and sensor resolution of 16 bits.</td>
<td>142</td>
</tr>
<tr>
<td>Table 10</td>
<td>Summary of single slope model N values for three separate data collection periods.</td>
<td>183</td>
</tr>
<tr>
<td>Table 11</td>
<td>Cumulative current consumption of wireless sensor module based on ratio of sleep and transmission times.</td>
<td>236</td>
</tr>
<tr>
<td>Table 12</td>
<td>Expected sensor battery life based on various commercial battery power capacities.</td>
<td>236</td>
</tr>
<tr>
<td>Table 13</td>
<td>MER values for Trial 1 with linear separation distances of 125 feet and 2 aisle way separations.</td>
<td>240</td>
</tr>
</tbody>
</table>
Table 14. MER values for wireless nodes in Trial 2. ......................................................... 241

Table 15. Summary of Message Error Rates for 12 nodes in extended duration study defined as Trial 2 with node 6 intentionally removed to increase the likelihood of message error. ........................................................................ 244

Table 16. Message error rate values for wireless nodes under configuration described by Trial 3. ..................................................................................................................... 246
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.</td>
<td>Bus sensor networking topology.</td>
<td>17</td>
</tr>
<tr>
<td>Figure 2.</td>
<td>Ring sensor network topology.</td>
<td>18</td>
</tr>
<tr>
<td>Figure 3.</td>
<td>Star sensor network topology.</td>
<td>19</td>
</tr>
<tr>
<td>Figure 4.</td>
<td>Mesh sensor network topology.</td>
<td>20</td>
</tr>
<tr>
<td>Figure 5.</td>
<td>Tree sensor network topology.</td>
<td>21</td>
</tr>
<tr>
<td>Figure 6.</td>
<td>Traditional measurement methodology for animal production facility.</td>
<td>52</td>
</tr>
<tr>
<td>Figure 7.</td>
<td>Energy transfer model for airflow from an agriculture ventilation fan.</td>
<td>59</td>
</tr>
<tr>
<td>Figure 8.</td>
<td>Simulation of vibration sensor signal output from initial motor activation ( t_0 ) to full speed fan operation ( t_1 ).</td>
<td>64</td>
</tr>
<tr>
<td>Figure 9.</td>
<td>Vibration sensor package, showing the wiring harness, status LED, and adjustment potentiometer.</td>
<td>68</td>
</tr>
<tr>
<td>Figure 10.</td>
<td>Typical mounting of the vibration sensor on the fan hood, nearest the greatest vibration source.</td>
<td>69</td>
</tr>
<tr>
<td>Figure 11.</td>
<td>Comparison of vibration sensor performance to pressure fluctuations in the manifold pressure of a compressor which simulates fan vibration.</td>
<td>71</td>
</tr>
<tr>
<td>Figure 12.</td>
<td>Regression analysis of sensor amplitude gain versus sensor internal temperature.</td>
<td>76</td>
</tr>
<tr>
<td>Figure 13.</td>
<td>Comparison of fan pressure drop to active vibration sensing and passive relay monitoring of ventilation status.</td>
<td>80</td>
</tr>
<tr>
<td>Figure 14.</td>
<td>Fan activity summary from 1000 head swine finishing facility. May 2006.</td>
<td>81</td>
</tr>
</tbody>
</table>
Figure 15. Digital vibration sensor circuit diagram. Schematic created in Altium Design Explorer, 2002 with manufacturing outsourced to Advanced Circuits, CO. ................................................................................................................................. 83

Figure 16. Example vibration output from the digital sensor showing differences in output magnitude between the fan inactive and fan active states. Output units are raw count values from the 0 – 5 V FSR, 8 bit analog-to-digital converter................................................................................................................................. 86

Figure 17. Histogram of fan vibration from a stage 2 fan measured with a digital sensor over a one week period................................................................................................................................. 87

Figure 18. Histogram of vibration data classified as active by a secondary fan rotational speed sensor................................................................................................................................. 89

Figure 19. Continuous vibration magnitude for single fan monitored with a digital sensor. A power supply failure occurred on May 14, 2007.... 90

Figure 20. Comparison of vibration magnitude from the digital vibration sensor to power supply voltage for three typical fan speeds......................... 93

Figure 21. Illustration of measurement errors causes by sampling intervals...... 95

Figure 22. Total fan on-time by ventilation stage for a representative poultry layer facility with tunnel ventilation fans in Ohio. ......................... 98

Figure 23. Percent ventilation by individual fan stage for a representative poultry layer facility with tunnel ventilation fans in Ohio. ................. 100

Figure 24. On events per day by ventilation stage for a representative poultry layer facility with tunnel ventilation fans in Ohio. ......................... 102

Figure 25. Daily median on-time and inlet temperature for a stage 1 fan in a representative poultry layer facility with tunnel ventilation fans in Ohio........................................................................................................... 103

Figure 26. An example timing diagram of minimum stage control period used in a ventilation control system of a tunnel ventilated poultry or swine building........................................................................................................... 104
Figure 27. Sampling diagram for $t_s = t_{on}$ assuming that no phase lag exists between the leading edge of the input signal and the sampling point. .................................................................105

Figure 28. Sampling diagram for $t_s = t_{on}$ with non-zero phase lag between the leading edge of the input signal and the sampling point..............106

Figure 29. Comparison of sampling errors versus fan startup and shutdown times for fan ontime and sampling time equal to 90 seconds..............108

Figure 30. Probability for 100% ventilation error based on startup and shutdown times causing a double sampling event for fan ontime and sampling time equal to 90 seconds.........................................................109

Figure 31. Sampling diagram for $t_s < t_{on}$ with zero phase lag between the input signal and the sampling point.................................................................111

Figure 32. Regression analysis of error versus the modulus of sampling time and fan ontime for cases of underestimation of ventilation time..............113

Figure 33. Regression analysis of error versus the modulus of sampling time and fan ontime and versus the sampling time for conditions of overestimation of error.................................................................114

Figure 34. Measurement error induced by sampling criteria for Stage 1 fans over a three hour duration in a high rise poultry layer facility..............119

Figure 35. Measurement error induced by sampling criteria for Stage 1 fan over a 12 hour interval in a high rise poultry layer facility.........................120

Figure 36. Measurement error induced by the sampling criteria for a Stage 1 fan over a 24 hour duration in a high rise poultry layer facility.................121

Figure 37. Network topology for a CAN bus sensor installation within a confined animal feeding operation.............................................................127

Figure 38. Logic pattern for recognition of recessive and dominant bits by a CAN bus transceiver.................................................................130

Figure 39. Schematic of benchtop CAN bus testing layout evaluated under bus lengths of 100 to 600 meters and data transmission rates of 50 to 250 kbits/sec.................................................................131
Figure 40. Graphical description of critical data transmission parameters for individual CAN bus message bits.........................................................................................................................131

Figure 41. CAN bus node placement along an external fan wall of a confined animal feeding operation......................................................................................................................138

Figure 42. CAN bus placement and connection to a vibration sensor used to monitor the activity status of a single speed exhaust fan at a confined animal feeding operation..................................................................................................................138

Figure 43. Time series plot of communication errors from node #3 during field testing of CAN bus data acquisition system..............................................................140

Figure 44. Expected path loss mechanisms within a CAFO................................................149

Figure 45. Reflective path loss model results for a flat surface and identical transmitter and receiver heights......................................................................................................155

Figure 46. Statistical summary for temporal signal strength variation in open air free space environment........................................................................................................165

Figure 47. Statistical summary for temporal signal strength variation in a poultry layer house with 1 aisle and 25 linear feet separation......................................................165

Figure 48. Regression model for path loss based on experimental RSSI data collected under free space conditions.........................................................................................166

Figure 49. Zigbee surface mount antenna radiation pattern. Reprinted from Figure 7.3 in Rufa 2.4 GHz SMD Antenna Datasheet, Antenova......................................................172

Figure 50. Angular antenna position impact on signal strength based on experimental RSSI values..........................................................................................................................173

Figure 51. Comparison of signal strength versus transmission distance for vertically and horizontally mounted wireless nodes within a single poultry aisle way..........................................................................................................................175

Figure 52. Statistical summary of path loss differences associated with plastic enclosure.................................................................................................................................177

Figure 53. Regression analysis for path loss within a single aisle on April 19th.180

Figure 54. Regression analysis for path loss within a single aisle on April 27th.181
Figure 55. Regression analysis for path loss within a single aisle on June 11th. 183

Figure 56. Graphical comparison of three regression models for estimating path loss within a single aisle. .......................................................... 184

Figure 57. Cumulative regression results for average of three separate sampling periods to predict path loss through a single aisle way in a poultry layer facility. .......................................................... 185

Figure 58. Interval plot and statistical summary of RSSI values for repeated measurements across a single fully stocked cage. .......................... 187

Figure 59. Interval plot and statistical summary of path loss values for repeated measurements across a single empty cage. ............................ 188

Figure 60. Statistical summary of path loss values for repeated measurements across two empty cages. .......................................................... 189

Figure 61. Statistical summary of path loss values for repeated measurements across two fully stocked cages. .................................................. 190

Figure 62. Regression results for wireless sensor path loss when elevated to 13 ft above the floor surface and within a single aisle. ......................... 191

Figure 63. Regression analysis output for path loss versus the log of transmission distance when transmitter and receiver were located 0.25 m above the floor surface. .......................................................... 193

Figure 64. Comparison of reflection model to standard path loss model. .... 194

Figure 65. Probability plot of predicted versus true RSSI values for floor reflection model within a single aisle way. .............................................. 195

Figure 66. Statistical summary of path loss values for measurement of diffraction across the top edge of two cages. ........................................ 197

Figure 67. Regression output for path loss through concrete structural divide versus separation distance. ......................................................... 198

Figure 68. Barn 3 actual path loss response in units of RSSI with the transmitter located stationary at the center point of the building. ............... 202

Figure 69. Scatterplot of Barn 3 model residuals versus separation distance. 204
Figure 70. Scatterplot of Barn 3 residuals versus the number of aisle separations.
......................................................................................................................................... 205

Figure 71. Regression analysis results for 2D spatial model with second order aisle term included................................................................. 206

Figure 72. Statistical summary of prediction model residuals after the addition of a second order aisle separation term........................................... 207

Figure 73. Scatterplot of Barn 3 prediction model after the addition of a second order aisle separation term.......................................................... 208

Figure 74. Matrix plot of Barn 3 path loss model input and residual terms........ 209

Figure 75. Regression analysis results for 2D spatial model with second order aisle term and interaction term included........................................ 210

Figure 76. Summary of residuals for Barn 3 path loss model after including an interaction term for log of separation distance and aisle separation distance....................................................................................................................... 211

Figure 77. Scatterplot of predicted versus true RSSI values based on the Barn 3 model including a second order aisle term and an interaction term.
......................................................................................................................................... 212

Figure 78. Barn 4 actual path loss response when measured with a stationary transmitter located in the center of the building and a movable receiver used to measure path loss in units of RSSI. .................................................213

Figure 79. Statistical summary of error in estimation of Barn 4 RSSI values from a predictor model developed based on a Barn 3 dataset.......................214

Figure 80. Matrix plot of input variables and residual values for comparison of Barn 3 model predictions, Barn 4 true values, and residuals..............215

Figure 81. Contour plot of error between Barn 4 actual path loss and predicted path loss based on the final predictor model........................................216

Figure 82. Variations in power consumption during transmission and sleep cycles of a wireless Zigbee sensor module.................................................234
Figure 83. Current consumption plot of a single message transmission from a wireless Zigbee sensor module. .................................................................235

Figure 84. Topology of wireless nodes in Trial 1. Node 13 was programmed as the network sink..................................................................................239

Figure 85. Topology of wireless nodes in Trial 2. Node 13 was programmed as the network sink..................................................................................242

Figure 86. Interval plot showing the bounds of the ANOVA results for a 95% confidence interval of the mean for wireless signal reception under Trial 2 conditions. Label format is Node ID – Location Number...243

Figure 87. Comparison of MER values for similar node topologies with 125 and 150 foot separation distances...........................................................................245

Figure 88. Topology of wireless nodes during Trial 3. ..................................................247

Figure 89. Individual value plot of delay time for each wireless node in Trial 3. Label format is Node ID – Location Number.........................................................248

Figure 90. Interval plot showing the bounds of the ANOVA results for a 95% confidence interval of the mean for wireless signal reception under Trial 3 conditions.................................................................249
## LIST OF EQUATIONS

<table>
<thead>
<tr>
<th>Equation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation 1.</td>
<td>Antenna gain based on an ideal lossless isotropic source (Bansal, 2004).</td>
</tr>
<tr>
<td>Equation 2.</td>
<td>Boundary of the near field region (Balanis, 2005).</td>
</tr>
<tr>
<td>Equation 3.</td>
<td>Radiation intensity calculation (Balanis, 2005).</td>
</tr>
<tr>
<td>Equation 4.</td>
<td>Radiation density (Balanis, 2005).</td>
</tr>
<tr>
<td>Equation 5.</td>
<td>Modified radiation density equation (Derived by Author).</td>
</tr>
<tr>
<td>Equation 6.</td>
<td>Friis path loss equation (Balanis, 2005).</td>
</tr>
<tr>
<td>Equation 7.</td>
<td>Expanded form of Friis path loss equation in decibel form (Derived by Author).</td>
</tr>
<tr>
<td>Equation 8.</td>
<td>Modified Single Slope path loss model (Derived by Author).</td>
</tr>
<tr>
<td>Equation 11.</td>
<td>Logarithmic representation of modified Friis path loss equation (Derived by Author).</td>
</tr>
<tr>
<td>Equation 13.</td>
<td>Accelerometer sensitivity (Derived by Author).</td>
</tr>
<tr>
<td>Equation 15.</td>
<td>Digital vibration sensor sensitivity (Derived by Author).</td>
</tr>
<tr>
<td>Equation 17.</td>
<td>Emission estimation error based on measurement of ventilation stage ontime (Derived by Author).</td>
</tr>
</tbody>
</table>
Equation 18. Emission error based on sampling error and input signal phase lag for synchronous ontime and sampling periods (Derived by Author)......107

Equation 19. Probability of 100% sampling error based on synchronous ontime and sampling periods (Derived by Author)..........................108

Equation 20. Emission error based on sampling error and input signal phase lag for cases of sampling periods greater than ontime periods (Derived by Author)..........................................................109

Equation 21. Emission error based on sampling error and input signal phase lag for sampling periods less than ontime periods (Derived by Author).....111

Equation 22. Calculation of transmission units for CAN bus networks (Derived by Author)........................................................................142

Equation 23. Expected path loss factors with a CAFO facility (Derived by Author)...................................................................................................149

Equation 24. Friis free space path loss model (Bansal, 2004)...............................152

Equation 25. Derivation of Friis’ free space path loss model based on unit gain conditions and operating within the 2.4 GHz frequency band (Derived by Author)..................................................................................153

Equation 26. Path loss calculation from reflected waves (Linmartz, 2001)........154

Equation 27. Diffraction path loss model equations (Bansal, 2004)..................156

Equation 28. Fresnel-Kirchhoff diffraction parameter (Bansal, 2004)...............156

Equation 29. Example calculation of diffraction path loss (Derived by Author)....157

Equation 30. Calculation of sample size to control confidence interval width for mean RSSI measurement (Derived by Author).........................167

Equation 31. Calculation of true antenna gain estimation for valid free space path loss model (Derived by Author).........................................................171

Equation 32. Confidence interval for regression parameters from April 19th aisle path loss test (Calculated by Author)........................................180

xxiii
Equation 33. Confidence interval for regression parameters from April 27th aisle path loss test (Calculated by Author)............................................................. 182

Equation 34. Confidence interval for regression parameters from June 11th aisle path loss test (Calculated by Author)............................................................. 183

Equation 35. Calculation of limit of the coefficient of reflection as the grazing angle approaches zero (Bansal, 2004).................................................................. 193

Equation 36. Corrected model for floor reflection path loss in poultry layer house with 0.25 m sensor heights (Calculated by Author)................................. 196

Equation 37. Wireless path loss link budget equation (Balanis, 2005)................................. 219

Equation 38. Modified link budget equation to include factor of safety for reliable wireless data transmission (Derived by Author)................................. 229

Equation 39. Path loss model within single aisle way of poultry layer facility (Calculated by Author)......................................................................................... 229

Equation 40. Two dimensional path loss model for poultry layer facility (Calculated by Author)........................................................................................................ 230

Equation 41. Calculation of wireless sensor power requirements when used in sleep mode (Derived by Author)................................................................. 250
CHAPTER 1

INTRODUCTION

Monitoring the air quality environment of confined animal feeding operations has become a high research priority due to the increase in gas and odor emissions that coincide with the physical growth of animal production facilities and a continued interest in animal and human worker well being. To accomplish dense sampling of environmental parameters over the large spans associated with such buildings, advances are needed in the area of sensor and sensor network design. Current monitoring methods use a central mobile lab location and install large lengths of wire and tubing to reach the far extents of each measurement point. Limitations exist in the maximum wiring distance as well as the flexibility of sensor layout after the installation is complete. High density sampling was rarely accomplished, because of the high cost associate with wire and sensor installation as well as the high data acquisition demands at the mobile lab caused by the increase in sampling density.

Technology has the ability to overcome many of these limitations by adapting smart sensors and sensor networking to the animal housing research area. As the cost and capabilities of microcontroller technology continue to improve, so does the
opportunity to distribute sensor processing power throughout the CAFO facility and no longer limit data collection by the configuration of the mobile lab. Technology advancements can also address the limitations in sensor placement flexibility by redefining the current philosophy of sensor installation and no longer relying on fully wired sensor solutions. By adopting wireless sensor networking technology, sensors can be placed directly at the ideal location and will greatly enhance researcher’s ability to design experimental plans to yield the greatest return of results. In order to address these issues in air quality monitoring, four main research objective were defined and are described in this document.

First, improvements will be made in sensing and recording ventilation rate information to improve the overall accuracy of emission calculations. Current sensors fail to provide the robust and reliable stage activity signal needed for high accuracy ventilation measurement. An energy model will be used to determine the optimal location for placement of a ventilation sensor. An embedded sensor will be developed solely for use as a ventilation monitor and will be optimized based on the environment presented by CAFOs. Testing will be conducted to evaluate the sensor’s ability to measure fan activity relative to other ventilation sensors used on previous research projects. Further modeling of ventilation systems will be conducted to evaluate the impact of sampling rate on the accuracy of stage type measurement systems. The outcomes of this model will provide predictor tools for future ventilation work and limit errors associate with data acquisition systems.

Secondly, wired sensor networks will be evaluated for their effectiveness in transferring sensor data over the long transmission distances typical in CAFO
environments. This will provide a means to reduce the data acquisition capacity of CAFO monitoring systems and provide researches with an improved flexibility when considering placement of sensing nodes. Specifically, the performance of a controller area network system will be characterized under extreme transmission distances. Physical and protocol based limitations will be defined and addressed as they relate to environmental sensing systems. Field experiments will be conducted to verify the performance of CAN nodes in representative CAFO system.

Thirdly, the performance of wireless sensor networks will be modeled and verified as they apply to sensing in poultry CAFO environments. Theoretical path loss models will be used to develop predictive models for specific causes of signal attenuation within CAFOs. The model outcomes will be verified through field experiments which will quantify the true path loss caused by many factors present within CAFO environments. A two-dimensional spatial path loss model will then be developed based on the results of the model verification results and this model will itself be evaluated through a comparison with an alternative poultry facility of similar design. Deviations between the model prediction and the experimental results will be reported in terms of decibel path loss differences. The outcome of this objective will be a fully verified model for use in the development of future wireless sensing systems and a classification of factors which negatively impact the ability to support wireless sensing within CAFOs.

Finally, a distributed wireless sensor network will be developed and evaluated to verify the reliability of such systems for CAFO environment monitoring. Network reliability will be evaluated by recording the error rate of specific network
sensors over extended recording periods. Network design considerations will be addressed as they relate to power consumption, distribution of sampling locations, mobility of sampling locations, and interconnection of multiple facilities. A case study will be documented for the extension of these results to other CAFO facilities including those used in swine production.

The results of these four objectives are presented in the following six chapters. Chapter 2 provides a full review of previous work in the areas of embedded sensor development, wireless sensor networking, and modeling of wireless environments. The conclusion of Chapter 2 brings forth a gap analysis of the current research literature and provides further justification for the need of continued research in this area. Chapter 3 discusses the design and testing of a new embedded sensor for improved monitoring of fan ventilation from CAFO facilities. This provided a classic demonstration of the potential improvements in sensing accuracy when embedded system technology is applied to animal environment monitoring. An extension of this work discusses the impact of sampling frequency on the accuracy of ventilation monitoring and provides recommendations for minimizing measurement errors.

Chapter 4 begins to address issues of multi-sensor networking by evaluating a Controller Area Network system for linking multiple vibration sensors within a CAFO. Through laboratory and field scale testing, CAN bus systems were found to be capable of covering the large transmission distance inherent to CAFOs, but still exhibited limitations in the flexibility of installation and sensor placement. Chapter 5 directly addresses this issue by evaluating the performance of wireless sensors in
CAFOs. No previous work had addressed issues related to wireless sensors within CAFOs, specifically signal path loss through the range of barn specific environmental factors. Theoretical models of path loss were compared to experimental path loss data and a set of path loss models were created to characterize the electromagnetic environment specific to layer poultry houses. These models were then used to create a two dimensional path loss model to predict path loss at any point within a poultry CAFO given the transmission distance and cage separation. This results of this chapter lead directly into Chapter 6, which presents the design of a full scale wireless sensor network for monitoring air quality parameters. Reliability was tested by monitoring the message error rates for individual networked sensors. Recommendations were made as the appropriate network design techniques and to methods for estimating a valid network factor of safety.

This work was then concluded in Chapter 7, which provided an overall summary of results for each previous chapter. A section on recommendations for future work was also included and should stand as a reference for future advances in the area of advanced sensing and networking in CAFO facilities.
CHAPTER 2

LITERATURE REVIEW

2.1. INTRODUCTION TO AIR QUALITY ENGINEERING

The goal of agricultural animal production facilities is to be economically viable, environmentally-friendly, socially accountable, and safe. Over the past two decades, livestock and poultry industries have evolved into a large scale, high mechanization, and concentrated animal feeding operations (CAFOs), which made animal production economically competitive. However, CAFOs have raised a significant challenge in environmental management, specifically management of animal waste and its impact on water and air quality. As the Environmental Protection Agency (EPA) continues to become stronger enforcers of water, air quality, and emission regulations Ohio producers will need to invest time and resources to closely monitor and control animal environments. Research in animal environment monitoring is vital to Ohio production agriculture due to the number of animals housed in confinement facilities and its economic impact on the state (Table 1).
### Ohio Production Statistics for Confined Animals

<table>
<thead>
<tr>
<th>Commodity</th>
<th>Live Animal Inventory (millions)</th>
<th>Market Value of Sold Agricultural Products (millions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poultry</td>
<td>$30.7</td>
<td>$604.8</td>
</tr>
<tr>
<td>Swine</td>
<td>$1.58</td>
<td>$322.7</td>
</tr>
<tr>
<td>Beef</td>
<td>$1.30</td>
<td>$408.2</td>
</tr>
<tr>
<td>Dairy</td>
<td>$0.48</td>
<td>$551.9</td>
</tr>
</tbody>
</table>

Table 1. Ohio animal production statistics. Source: NASS, 2002.

Understanding the animal environment and air quality is a crucial first step in maintaining healthy and productive livestock as well as ensuring the health of employees within the agriculture sector (Arogo et al., 2003). The EPA has issued reports concerning the negative impact of air quality and air emissions from large animal production facilities and has stated that continued research must be performed to accurately quantify their effects (EPA, 2001).

Advanced electronic and automated systems have been through significant developments and have played a significant role in the advancement of multiple focus areas of Biosystems and Agricultural Engineering. Farm machinery automation has provided numerous advancements in data collection and control in production agriculture (Reid et al., 2000). Many of the systems used to implement “precision agriculture” methodologies are based on inexpensive and dedicated microcontroller systems. Microcontroller based control and data acquisition systems are also growing rapidly in soil and water based applications such as soil moisture monitoring (Valente et al., 2002) and plant environment control (Brown and Lacey, 2002). Further application of these microcontroller and networked
embedded sensor technologies will release the limitations of current monitoring methods and set an important platform for animal production industries to achieve a new level of precision and environmental stewardship.

The importance of air quality information and the sheer number of physical sensors at a monitoring site along with the need for increased sampling density requires the use of advanced sensor networking technologies in animal production environmental monitoring. Sensor networks will allow many commercially available sensors to be controlled and monitored from a single location. This would address the current deficiency in air quality monitoring systems, which is the lack of an inexpensive and reliable means to network multiple sensors and allow for rapid data collection. Sensor networks will enhance environmental air quality monitoring by allowing sensing nodes to be located in precise locations, allowing as many sensors as necessary to be installed within a facility, reducing the overhead installation cost, and allowing for rapid adjustment of sensor locations to adapt to changes in the measured environment.

2.2. EMBEDDED SENSORS FOR AGRICULTURAL SYSTEMS

2.2.1. Embedded Sensors

Embedded systems have been used to improve grain quality by accurately tracking the number and size of insects in grain storage bins (Shuman et al., 2004). The sensor node used an infrared light beam emitter and receiver to detect the passing or movement of insects. A microcontroller system was installed local to the sensor and recorded the insect activity. This information was then relayed back to a
central computing network and was used to schedule pest fumigation. Fumigation effectiveness could also be directly monitored by the embedded sensor in a much safer manner than the alternative method, which required a person to enter the storage facility.

Improvements in greenhouse spraying equipment were demonstrated when an embedded control system was able to automate the process, thus removing the operators from contact with dangerous pesticides (Singh et al., 2005). The robotic sprayer used a Tern microcontroller (Davis, CA) to measure the distance between greenhouse aisle ways and employed a fuzzy logic control structure to manipulate the steering system. Results showed the ability to guide a small robotic sprayer within 1 cm on a concrete surface and within 2.5 cm on a loose sand surface.

Single board computers linked through a Controller Area Network (CAN) bus network was successful in identifying weeds in real time while traveling though a field (Wei et al., 2001). Distributed nodes were also able to control individual nozzles and apply herbicides as well as generate a field-level weed map. Results indicated that the CAN bus sensor network was very applicable for machine level control, provided ample bandwidth for data transmission, and exhibited a minimum transmission latency.

Embedded systems have been implemented to accurately detect and count the number of dumping events where fruit was transferred from a harvest bin into a storage truck with an accuracy of greater than 98% (Tumbo et al., 2002). A microcontroller based system was interfaced to a GPS receiver, a flash memory card, two limit switches, a buzzer; and a counter and was used to track the yield of citrus
fruit. This system was installed in a harsh environment and demonstrated microcontroller’s rugged capabilities when implemented into a properly designed embedded system.

Animal movement in a pasture environment can be recorded by an embedded data logger linked to a microcontroller system (Davis et al., 2005). The Herd Activity and Welfare Kit (HAWK) was based on an 8-bit microcontroller that interfaced with a 12-channel, WAAS corrected, low-power GPS receiver and a Compact Flash memory card. The HAWK was enclosed in a sealed housing and was deployed for over thirty days before battery recharging was necessary. Information collected from this device is providing a better understanding of the grazing patterns and physiological comforts of grazing animals.

2.2.2. *Networked Embedded Sensors*

Networking embedded sensors is accomplished by allowing for electronic communication between two or more remote sensors connected by a transmission media. The method of data transfer, synonymous with a spoken language, can be either based on a standard or proprietary protocol. Standardized protocols are advantageous in that embedded sensors from multiple brands can intercommunicate, but can provide limitations in that the transmission scheme is not easily manipulated. A proprietary communication standard can provide the exact specifications required for a successful communication network, but will be inaccessible from other embedded equipment. This inaccessibility can be an additional level of security for sensitive data networks.
A distributed wireless irrigation monitoring system was designed and installed with real-time control of 1850 hydrants (Damas et al., 2001). This system used a two-wire communication network in a tree topology to access information from multiple field installed water hydrants. Each regional network branch was then connected back to a main computer workstation via an UHF radio link. Results showed a 30 – 60 % reduction in water savings, higher crop productivity, and optimum use of fertilizers.

Darr el al. (2004) demonstrated the use of a CAN bus based distributed control system for autonomous vehicles. Our system linked seven microcontroller based nodes along a CAN bus system and controlled the functionality of a fully autonomous vehicle.

Mitchell (1999) has described a systematic approach to internetworking of multiple buildings and equipment at the Southeast Poultry Research Laboratory operated by the United States Department of Agriculture. This application used a LonWorks open communication protocol to interface several facilities whose current communication infrastructure was uncommon. This allowed for the bridging of such protocols as Ethernet, TCP/IP, Optomux, Modbus, CAN, RS232, and RS485. They have reported improvements in monitoring and control of critical environmental and security related parameters as well as an decrease in notification latency when reporting fault conditions.
2.2.3. **Point-To-Point Wireless Embedded Sensors**

Point-to-point communication occurs when the end node can only transmit data to a single master or synchronization node. In Star networks, which are common multi-node point-to-point communication systems, each individual end node can only transmit data back to the central master node. Data transferred from one end node to another must first pass through the central master before being rerouted to its final destination point. Dynamic impacts sustained by perishable fruits and vegetables during processing have been quantified by a unique application of embedded systems (Geyer et al., 2006). They reported the development of a microcontroller based wireless transmitter that actively reported acceleration data in all three dimensional axes of the sensor. When placed directly into fruit before processing the impacts imposed by handling and packaging could be measured and solutions brought forth to reduce the magnitude of these impacts. This sensor utilized a proprietary point-to-point radio communication and provided continuous acceleration feedback at a rate of 3200 samples per second. The nominal wireless transmission range of the device was 15 meters and by fully encapsulating the sensor in an epoxy resin, it was sealed against fruit acid based corrosion.

Unique network protocols have been developed for intercommunication of field sensors and control equipment for center-pivot irrigation systems (Wall and King, 2005). This protocol required only 5 bytes of the network packet for data routing, thus was more network efficient than the majority of previously developed systems. Wireless, land based sensors were shown to communicate with the active
center-pivot irrigation system through an ad-hoc connection. As the center-pivot system approached the ground based nodes, the nodes would create a network connection and transmit their sensor data. This sensor data was then used to adjust the input water prescription in that site-specific zone. To communicate information back to the main control station, located at the rotational point of the center-pivot system, a power line carrier communication (PLCC) based local area network was implemented. The authors indicated that they choose the PLCC because of its low application cost. The final version of this protocol, named AG-NETS, provided a very high 81% efficiency in data transmission, but only allowed real-time access to wireless sensors within close proximity of the traveling irrigation system.

Protecting humans from dangers caused by autonomous vehicles is a major concern with their operation. A wireless embedded system has been developed to help identify humans in the near proximity as a means to redirect autonomous type vehicles when they come in contact with people (Chung et al., 2001). This system relies on wireless receivers and transmitters along with GPS location information to triangulate the individual location of humans near the autonomous vehicle who are equipped with specially designed security helmets. This system was designed to identity humans wearing the customized helmets and cannot recognize pedestrians or humans who are not equipped with this position feedback device.

Wireless data loggers enhance the setup and positioning of air environment monitors within livestock facilities (Wheeler et al., 2001, and Morais et al., 1996). The installation of small dedicated data loggers was shown to improve the cost and feasibility of sustainable long term studies. A point-to-point proprietary data
A patented wireless temperature transmitter was used by researchers at the University of Florida for monitoring the internal body temperature of dairy animals (Hicks et al., 2001). The sensor, which was the size of a small pill, was ingested by the animal and passed through the animal digestive system. While imbedded, the crystal oscillator sensing mechanism would oscillate at a frequency proportional to the temperature of its surrounding environment. This variable frequency signal is transmitted wirelessly and received by a data logger located in close proximity to the animal. Data is downloaded from the data logger through an RS232 computer connection. Research has shown this method to be very effective in monitoring the core body temperature of animals, but has only been used as an explanation tool rather than a real-time predictor of animal health (Davis et al., 2003).

Embedded systems have also been applied to direct research in monitoring of animal nervous systems (Silva et al., 2005). A wireless node was developed to monitor the cortical electroencephalogram of bovine animals, which has been found to be sensitive to environmental heat (Sinha, 2003). The node consisted of three core components; signal amplification of the cortical electroencephalogram signal, digital conversion of the signal by a microcontroller based analog to digital converter, and transmission of the digital data back to a base location. A point-to-point star network system was installed, which used a computer based router to
interface with each roaming animal within the barn facility. The wireless
transmission was enabled by a commercial 433 MHz wireless radio transceiver.

2.3. NETWORKING OF AGRICULTURAL SENSORS

2.3.1. DEFINITION

Sensor networks are defined as multiple intelligent devices (embedded
systems), which are interconnected through a communication medium. Sensor
networks have the ability to both collect and record data from analog or digital
sensors and can be equipped to operate control systems through analog and digital
output channels. The host processor capacity of sensor networks can range from
simple embedded microcontrollers to advanced super computers.

Sensor networking is also not a new concept as it applies to agriculture.
Various mechatronic research groups have implemented sensor networks over the
past several years (Stone et al., 1999, Tian et al., 1999, and Darr, 2004). These
groups have proven that reliable sensor networks can be developed in the harshest
of operating conditions.

Each device connected to a sensor network is defined as a node or electronic
control unit (ECU). Active nodes require three key components. The first
component is an embedded system that encompasses the host processor, voltage
regulation, signal conditioning, and peripheral operation devices (Perkins et al.,
2002). The second component is a transceiver that acts as a gateway between the
embedded system and the communication medium. A transceiver is a combination
of a transmitter and receiver module which allows for bi-directional communication.
When lower level nodes are required, it is common that the transceiver element be replaced with a transmitter only to reduce cost and power consumption. The final component is the communication medium itself. The communication medium in which nodes pass information can be through a wired connection, a wireless radio transmission, or through other means such as light transmission through fiber optic cables and infrared wireless transceivers.

Wireless networking technologies are continuously evolving and available in many forms. Differences among networking systems are defined by the hardware and software protocols used and are typically measured by the transmission frequency, range, modulation method, power consumption and bandwidth of the transceivers. All wireless networks are made of individual nodes that have the ability to inter-communicate through wireless means. Advanced nodes will also incorporate sensor and memory technology directly onto the remote node. This addition allows the remote device to collect, store, and transfer physical parameters associated with the environment surrounding the node.

Enabling a device to communicate wirelessly for point-to-point communication is straightforward for general purpose operations. Many manufactures supply a wireless transmitter to send serial data wireless from one computer to another (Radiotronix 2005, MaxStream 2005, & B&B Electronics 2005). These devices utilize standard wireless transceiver technology to exchange data at baud rates of up to 128k bits/second. They typically operate in either the 900 MHz or 2.4 GHz unlicensed band that is set aside for industrial, scientific, or medical
ISM applications. As the frequency of the wireless signal increases, the wavelength decreases, which decreases the travel distance of the wireless signals.

The tradeoff for the enhanced transmission length of a 900 MHz system is a reduction in the bandwidth capacity of the signal. Higher frequency transmissions can encode higher data rates, which will allow an increase in data transfer through a wireless network.

2.3.2. Topologies

The formulation of sensor networks requires an architecture to define how the individual nodes will communicate. The means in which the nodes communicate (wired versus wireless) is completely independent of this architecture. Common networking systems can be broken into five separate architectures; Bus, Ring, Star, Mesh, and Tree.

Bus topologies rely on a central communication line to transmit data (Figure 1). Each active node will transmit a broadcast message which all other nodes will see. Software and hardware filtering are required to ensure messages are properly received by their intended target. Controller Area Networks are a common implementation of bus networks for machine control operations.

![Bus sensor networking topology.](image)

Figure 1. Bus sensor networking topology.
Bus topologies are reserved for wired communication only. They require the ability to overwrite or assert dominant communication bits over top of recessive bits. While this is possible in a wired communication medium, signal latencies involved with modulating and demodulating wireless signals prevent it from being used with a wireless protocol.

In Ring networks each node has only two neighbors (Figure 2). Data is transmitted in only one direction around the Ring and each node must accept the new messages, determine if they are the intended recipient, and retransmit the message to the next neighbor on the bus. Although not used commercially very often, one key advantage of Ring networks is that they have inherently very long transmission ranges. Since each message is received and then rebroadcasted at each node, the strength of the signal is rejuvenated at each node. This essentially eliminates the signal attenuation that is common to extremely long single bus networks.

Figure 2. Ring sensor network topology.

Ring networks may be implemented either through wireless or wired means. When implemented wirelessly, additional software precautions must be taken to
only transmit the messages in a single direction. This is critical when nodes are within wireless range of multiple other nodes. For this reason, wired networks are typically preferred for Ring implementations.

Star networks use a single point of contact to allow multiple nodes to communicate (Figure 3). The outer nodes are slave devices and pass all intercommunications through the network hub or router device. Star networks are commonly used for office personal computer networking and for embedded control networking of peripheral devices. One advantage of Star networks is that if a wired connection is destroyed only the connected node is dropped from the network. For Ring and Bus systems, a wiring fault can cause all network communications to fail. A major disadvantage of this system is that if a fault occurs at the router, all communication fails within the entire network.

![Star network topology](image)

Figure 3. Star sensor network topology.

Star communication can be implemented either through wireless or wired protocols. Either is equally satisfactory, but both are still limited to direct communication between a node and a router. No direct communication between two nodes is permitted.
Mesh networks allow for a higher degree of communication reliability by providing individual nodes with multiple transmission paths (Figure 4). The nodes themselves also act as routers and can enable widely distributed networks by continually repeating the data messages. This feature is very similar to the retransmission feature of a ring network. As new nodes are added to a mesh network the routing paths are reconfigured to include the new devices and allow them full access to the network. This topology is highly adaptable and is widely used in applications where a widely distributed network is required and no previous networking infrastructure is in place. The negative impact of such a failsafe network though is that since each message is being retransmitted many times as it passes along the network, the transmission time of the message can be quite delayed and the overall bandwidth of the network is lower than more traditional topologies.

![Figure 4. Mesh sensor network topology.](image)

Mesh networks are limited to wireless communication protocols due to the extreme level of physical wiring required for wired implementation. They offer wireless nodes the unique ability to intercommunicate from any two nodes rather than requiring an intermediate router.
Tree networks are a blend of bus and star networks (Figure 5). This architecture commonly uses a three-tiered communication hierarchy. A single bus links several master nodes along the tier 1 path. These nodes then communicate directly with several tier 2 nodes which are distributed along the bus. Each tier 2 node then communicates with multiple tier 3 nodes. The tier 3 nodes will be interfaced with the sensor and control systems and provide the information back through the network. When implemented wirelessly, the tier 3 nodes are often battery powered and enter a low power mode between transmissions. This allows for a high reduction in power consumption and lets nodes be deployed for long durations of over 1 year.

Figure 5. Tree sensor network topology.
2.3.3. **WIRED SENSOR NETWORK PROTOCOLS – CONTROLLER AREA NETWORK**

Robert Bosch GmbH designed the Controller Area Network in 1986 upon request by Mercedes to develop a system that would allow for communication between three electronic control units (Bosch, 1991). It was noted that a standard UART communication could not complete the task because it only allowed for point-to-point communication. Although the CAN bus was originally designed for automotive applications, it has been applied to many areas of automation and control. CAN has been used in applications including warehouse shipping automation, packaging machines, medical devices including X-ray collimators and patient tables, and building controls including alarm and sprinkler systems (CAN-CIA). The unique aspect of a CAN network is that each message is preceded with an identifier that is unique to the transmitting controller and that multiple controllers can communicate over a single two-wire bus. Two wires are required for the node to assert the two different voltage levels defined by the CAN protocol. If two messages are sent simultaneously, an automatic arbitration process ensures that the highest priority message is sent first. The lower priority message then has the opportunity to retransmit upon completion of the first message. Incoming messages are filtered by the ECUs based on the unique message identifier of the sender (Bosch, 1991).

There are three separate CAN standards: CAN Version 1.0, Version 2.0A (Standard CAN), and Version 2.0B (Extended CAN). The main difference in the three standards is the length of the identifiers that precede each message. All work presented in this publication is based on the CAN 2.0B standard.
2.3.4. Wireless Network Protocols

**IEEE 802.11 Wireless Ethernet**

IEEE 802.11 (1999) was initially developed for use with personal computers as a replacement for a traditional Ethernet cable. This protocol has undertaken several iterations, mainly to modify the operating frequency and enable higher data transfer rates. Currently, IEEE 802.11 g is the industry standard for wireless hotspots and remote wireless internet access. Data transfer rates of 54 Mbps in the 2.4 GHz ISM band are sustainable with the IEEE 802.11 g protocol. WiMAX is another form of the expanding wireless Ethernet field. With a potential transmission range of 50 km and a maximum data rate of 70 Mbps when in close rate, WiMAX offers many advantages when compared with alternative systems. Current US adoption has focused on the 2.4 GHz spectrum as an ideal operating range, although lower frequencies are being considered due to their potential for increased transmission distances.

**IEEE 802.15.1 Bluetooth**

IEEE 802.15.1 (2002) or Bluetooth is a wireless standard targeted for short range communication of portable personal devices. Common uses of Bluetooth technology include laptop computer, cellular telephones, and Personal Digital Assistants (PDAs). Current Bluetooth implementation also operates in the 2.4 GHz ISM band and supports a data transfer rate of 3 Mbps. Bluetooth, like 802.11 can be configured in an Ad Hoc network, which allows two node devices to directly communicate and transfer data without having to pass through a router or base.
station and allows the nodes to create associations with one another whenever they are within transmission range. Multiple Bluetooth nodes can be configured into a small network known as a piconet. This is a Star network formed by one master and multiple slave units. The limitation of this network type is that each remote node must be within the set transmission distance of the master. This makes it difficult to expand the network range beyond a tight perimeter area.

**IEEE 802.15.4 Zigbee**

IEEE 802.15.4 (2003) or Zigbee standard was targeted for low cost, high density, long battery life wireless networking that supported a full mesh networked protocol. Zigbee networks feature a “self healing” mesh topology. If data cannot reach its destination through an intended link, the network dynamically routes that data to make delivery through an alternate path. While this capability existed previously in proprietary technologies, Zigbee delivers it in low-cost, standardized devices.

The main advantage of mesh networking is an ability to extend the communication network well beyond the standard transmission range of the nodes. The Zigbee standard operates in the 2.4 GHz ISM band and supports a data rate of 250 kbps. Due to the much lower data transmission rates, Zigbee networks are tailored more towards sensor and data acquisition networks rather than consumer devices which would require streaming audio and video capabilities. Two types of nodes are defined within the Zigbee protocol. Full-function-devices (FFD) are higher level devices which handle routing, coordination, network formations, and
other network functions. Due to their network responsibilities, these nodes must remain active at all times and thus typically have higher power consumption rates than other nodes. The second type of Zigbee node is defined as a reduced-function-device (RFD). RFD's are typically viewed as simple sensor nodes which have no responsibilities related to networking topology or coordination. Furthermore, RFD’s can only communicate to other nodes through FFD’s and can be placed in a low power mode between data transmission events. Hybrid Zigbee networks are made up of a series of FFD’s and RFD’s. The RFD's act as a small Star network around the FFD’s. The FFD’s then function as a self contained mesh system.

Commercial implementation of Zigbee type mesh networking is available under Dust and Mote trade names. These and other companies are offering mesh networking capabilities and peripheral sensor boards for common parameters such as temperature, acceleration, and light intensity. These commercial systems do though have significant limitations with regards to data acquisition resolution and transmission capacity in agricultural applications (Goense and Thelen, 2005).

**Radio Frequency Identification**

Radio Frequency Identification (RFID) technology has seen a variety of applications in food processing and safety, product identity preservation, and inventory management (Hamrita and Hoffacker, 2005, and Nichols, 2004). RFID is classified into two categories, passive and active systems. Passive systems are the most miniaturized form of wireless technology and are commonly embedded into bar codes and other identity preservation devices for less than $0.01 per unit. These
devices contain a small amount of non-volatile memory along with a simple embedded controller, antenna, and power storage device. Passive tags do not have battery power, so they must be interrogated by an RFID reader, which exposes the tags to a constant RF signal. The power from this signal is captured and stored as electrical energy, which for a short period of time can power the embedded controller and allow it to transmit the tag identification data. These passive devices can only transmit data over very short ranges, with most commercial systems being under 2 meters. Furthermore, since there is no permanent battery source, the passive RFID device has no capacity for continuous data acquisition.

Active RFID tags are slight modifications from passive tags, with the main difference being an imbedded battery, which allows the tag to collect continuous sensor data. These tags are widely used in the food industry and have been successfully used to verify shipping conditions of a variety of perishable items. Active tags also have an increased transmission distance, but require more maintenance due to battery charging requirements and are significantly more expensive on a per unit basis. Like passive tags though, active tags are only used for point-to-point communication and have little ability to be interconnected in any type of network topology.

2.4. APPLICATIONS OF WIRELESS SENSOR NETWORKS

2.4.1. Wireless Ethernet

Guo and Zhang (2002) used an IEEE 802.11 protocol to synchronize the operation of tractors running in close proximity within an agricultural field. This
system was also successful in transmitting data, but also exhibited high current
draws that required a constant power generation source.

A similar device has been used and incorporated into an automated grazing
system for bovines (Butler et al., 2006). Their system communicated via a WiFi
network to record the position of animals within a pasture area and used sound
alarms to herd grazing animals in a specific direction. Although the embedded
system portion of this project worked successfully, the authors were not able to
show significant control of animal herding.

2.4.2. Bluetooth

Kim et al. (2006) demonstrated a more advanced system for irrigation
monitoring that allowed for real time access to field conditions. This system utilized
the Bluetooth protocol with a high gain patch antenna and could deliver sensor
network data up to 700 meters away with a radio power consumption of nominally
65 mAmps. Each field node was instrumented to measure soil moisture, soil
temperature, and air temperature. The sensors were self powered via a solar panel.
A host computer acted as the router within this star network and collected data
individually from each node. This information in addition to local weather station
data was used by the host computer to improve irrigation scheduling.

Nagl et al. (2003) also developed a sensor platform for cattle monitoring, but
included more specific health monitors including a pulse oximeter as well as a point-
to-point wireless link through a Bluetooth connection.
2.4.3. **ZIGBEE**

Zigbee and its mesh networking predecessors have seen many recent applications since their initial release and development in 2004. The first commercial mesh network nodes (also known as motes) were produced and distributed by Dust Networks, Inc. Promotional literature from this company has outlined many applications where wireless mesh networking technology has been advantageous. The first of these is a reduction of machinery downtime using distributed wireless monitors for predictive maintenance in industrial applications. SmartMesh sensors allow data collection on a continuous basis without human intervention which reduces labor costs while increasing data quality. SmartMesh technologies have also been shown to improve the energy efficiency of buildings by providing environmental sensor data at locations previously unattainable. Data suggests that the average building energy consumption increases at a rate of 17% every 2 years. A reduction in this increase through enhanced automation can pay strong dividends for industry adopters. Finally, SmartMesh sensors can provide improvements to commercial building security by improving the granular coverage of sensors for hazardous materials and by providing a low cost solution to tracking of capital equipment items.

2.4.4. **Radio Frequency Identification Devices (RFID)**

RFID systems have been used to successfully track the movement of course sediment following runoff events in southeastern Arizona. Nichols (2004) reported imbedding commercial RFID transponders within simulated coarse sediment
particles and using a reader to located the particles after they were displaced during a runoff event. The new location of the particles was measured using a real-time kinematic geopositioning system and logged for future analysis. The overall recovery rate of displaced particles was 96%.

Another application of RFID in environmental monitoring was the development of a smart wireless soil monitoring sensor that could be buried under the soil surface and report soil temperature information through a 13.56 MHz passive RFID tag (Hamrita and Hoffacker, 2005). This sensor also included an embedded Motorola 68HC11 microcontroller and integrated circuit thermometer to complete the embedded system. Lab results showed a high correlation between the RFID reported temperature and measurements obtained by a traditional thermocouple. Limitations were acknowledged; specifically a maximum transmission range of less than one meter, but this could be overcome in situations where heavy field activity is normal such as center pivot irrigation systems.

2.4.5. Cellular

Geers et al. (1998) introduced a protocol and management system for an autonomous tracking system to monitor transport of animals. Named TETRAD, the system was aimed at both improving animal disease prevention and enabling improved monitoring of animal welfare during transport. Onboard the animal transport unit the identification, body temperature, and GPS position of each animal was tracked via a mobile computer. This information was relayed back to a database through a GSM cellular phone connection. The cellular phone interface decreased
infrastructure cost due to the wide adoption of cellular technologies but did limit the
data throughput capacity.

2.5. MODELING PERFORMANCE OF WIRELESS SENSORS

2.5.1. BACKGROUND FUNDAMENTALS

Fundamentally, the transmission of wireless data is no different from the
transmission of data through normal wire-based modes. Wireless systems simply
use air, water, atmosphere or other types of media rather than electrical wire.
Rather than inducing voltage changes across a transmission wire, wireless systems
use antennas to propagate or radiate electromagnetic fields from the transmitter to
the receiver.

In order to develop radiation from an antenna, there must be a time-varying
current or acceleration/deceleration of charge. This change in velocity of charge can
occur due to bends or discontinuities in transmission lines, terminated transmission
lines, or truncated transmission lines. By energizing a transmission line, charges are
accelerated in the source end of the wires and rapidly decelerated near the near the
end of the wire. The initial acceleration of charge is accomplished through the
source driver of the wireless system, while the deceleration component is
dependent on the internal forces induced by the buildup of charge near the end of
the transmission line. Also, since the radiation element is driven by the changing in
current of a transmission line, the driving source for radiation must be pulsating or
sinusoidal in nature.
The pattern of radiation produced by an antenna is defined as the mathematical function or graphical representation of the radiation pattern. The radiation field patterns are typically displayed on a logarithmic or decibel scale to highlight areas of poor radiation performance. Antenna performance patterns can include both major lobes and minor lobes, representing various magnitudes of performance based on the angular position relative to the antenna. Isotropic radiators exert equal radiation in all directions and are only used as a hypothetical comparison against real antennas. Directional antennas have a distinct preference towards radiating waves in one or more defined directions. Omnidirectional antennas allow for a non-directional pattern in at least one plane.

The relative gain of an antenna is defined as the ratio of the power gain in a given direction to the power gain of a reference antenna in its referenced direction. This reference antenna gain is calculated based on an ideal lossless isotropic source (Equation 1).

\[ G(\theta,\phi) = e_{cd} \left[ 4\pi \frac{U(\theta,\phi)}{P_{rad}} \right] \]

Equation 1. Antenna gain based on an ideal lossless isotropic source (Bansal, 2004).

Where: 
- \( G(\theta,\phi) \) = Gain at a given angular direction (unitless)
- \( e_{cd} \) = Antenna radiation efficiency (unitless)
- \( U(\theta,\phi) \) = Radiation intensity at a given direction (dB)
- \( P_{rad} \) = Total radiated power (dB)
For antennas that have highly directional characteristics, it is realistic to have radiation intensities greater than the total radiated power, thus creating gains higher than one.

Electromagnetic fields are radiated differently depending on the proximity to the antenna. The near-field region is defined as the area surrounding the antenna where radiation fields predominate and the field distribution is highly dependent on the distance from the antenna. If an antenna has a maximum dimension that is not large compared to the wavelength of the transmitted wave, then this region may not exist. The boundary of the near field region from the center of the antenna can be described as (Equation 2):

\[ R_{nf} = 0.62 \sqrt{\frac{D^3}{\lambda}} \]

Equation 2. Boundary of the near field region (Balanis, 2005).

Where: \( R_{nf} = \) Distance to the near field boundary

\( D = \) Maximum antenna dimension

\( \lambda = \) Wavelength of radiated signal

Note: All variables must be in represented in the same unit of length.

The far-field region at the boundary of the near-field and is defined as the area where the angular field distribution is constant and not affected by the distances from the antenna. Given that optimal antenna design occurs when the length of the antenna is a fraction of the incoming wavelength to produce resonance
within the antenna unit, it can be shown that the near-field region is quite small and that the far-field region will dominate the transmission range.

Measurement of antenna radiation within the far-field range is conducted by calculating the radiation intensity. Radiation intensity is the power radiated from an antenna per unit of angle (Equation 3). This is calculated as the square of the distance of interest times the radiation density. Radiation density is a measure of the power density and is calculated as the cross product of the electric field vector and the magnetic field vector (Equation 4).

\[ U = r^2 \cdot W \]

Equation 3. Radiation intensity calculation (Balanis, 2005).

Where:

- \( U \) = Radiation intensity (W)
- \( r \) = Distance to measurement point (m²)
- \( W \) = Radiation power density (W/m²)

\[ W = E \times H \]

Equation 4. Radiation density (Balanis, 2005).

Where:

- \( W \) = Radiation power density (W/m²)
- \( E \) = Electric field vector (V/m)
- \( H \) = Magnetic field vector (A/m)
Thus, the radiation intensity can be calculated as (Equation 5):

\[ U = r^2 \cdot [E \times H] \]

Equation 5. Modified radiation density equation (Derived by Author).

Antenna radiation density can be measured experimentally while placed inside an anechoic chamber, which minimized disturbances caused by natural surroundings and other wireless devices. While radiation density is a useful property when selecting an antenna, it is difficult to measure when placed in a non-ideal environment. To distinguish antenna power and thus transmission strength in a true application the degradation of signal caused by the environment must be quantified. Three popular methods exist to measure the transmission power in a true environment. These include Signal-to-Noise Ratios (SNR) and Relative Signal Strength Indicators (RSSI). Signal-to-noise ratio is the ratio of desired signal content to the amount of background noise received by the wireless unit. SNR is calculated as the power in the desired frequency range to the power in other near proximity ranges. RSSI is simply an indication of the received signal power within a desired band. RSSI provides no information on the quality of the received data or if the data may be transmitted from a noise source.

The effectiveness of wireless sensor communication is directly related to the capacity to transmit electromagnet radiation through the sensor environment. All environments exert some level of path loss, or degradation to the radiated signal, and quantifying the level of loss from different environmental factors will enable
more effective designs of sensor networks in the future. The most basic wireless environment assumes the transmitting and receiving antennas are separated in free space by some finite distance and that the antennas are within clear line-of-sight of one another. It further assumes that the antennas are isolated from any other surfaces that may reflect or otherwise induce electromagnetic noise. Based on these assumptions, the Friis equation for generic line-of-sight transmission loss is (Equation 6):

\[ P_r = G_r G_t \left( \frac{\lambda}{4\pi r} \right)^2 P_t \]

Equation 6. Friis path loss equation (Balanis, 2005).

Where:

- \( P_r \) = Power received (dB)
- \( P_t \) = Power transmitted (dB)
- \( G_r \) = Receiving antenna gain (unitless)
- \( G_t \) = Transmitting antenna gain (unitless)
- \( r \) = Separation distance of the antennas (m)
- \( \lambda \) = Wavelength of the signal (m)

A common derivation of this power equation is to represent the power level as a ratio of power received to power transmitted and report this ratio in decibel units (Equation 7).
\[
\frac{P_r}{P_i}(dB) = 10\log \left[ G_r G_t \left( \frac{\lambda}{4\pi r} \right)^2 \right]
\]

\[
\frac{P_r}{P_i}(dB) = 10\log \left[ \frac{G_r G_t \lambda^2}{(4\pi)^2} \right] + 10\log \left[ \frac{1}{r^2} \right]
\]

\[
\frac{P_r}{P_i}(dB) = 10\log \left[ \frac{G_r G_t \lambda^2}{(4\pi)^2} \right] + 10\log [r^2]
\]

\[
\frac{P_r}{P_i}(dB) = 10\log \left[ \frac{G_r G_t \lambda^2}{(4\pi)^2} \right] - 20\log [r]
\]

Equation 7. Expanded form of Friis path loss equation in decibel form ( Derived by Author).

The first term in this equation is based strictly on the antenna gains and wavelength of the signal. This will be a constant for a particular wireless link and is independent of the environmental surroundings. The second term describes the path loss within a free space environment and is dependent on the separation distance between the receiver and transmitter. When free space does not exist between the receiver and transmitter it is common to modify this equation by adding an efficiency factor to the second term. This factor will cause an increase in signal decay as it travels through a specific medium. In its reduced form, this model is referred to as the Single Slope Model due to its simplification of parameters (Equation 8).
\[
\frac{P_r}{P_i} (dB) = 10 \log \left[ \frac{G_i G_r \lambda^2}{(4\pi)^2} \right] - N \cdot 10 \log [r]
\]

Equation 8. Modified Single Slope path loss model (Derived by Author)

Where: \( N \) = Efficiency factor (unitless)

The efficiency factor is known to be 2 when in free space. The greater the value of \( N \), the greater the rate of signal decay through a medium. \( N \) can be less than 2 and thus better than the free space condition when a network connection exists in an amplifying environment such as a solid hallway that acts as a signal waveguide.

As expected, as the distance between two antennas increases, the power received will decrease. Also, as the frequency of the signal increases, the power received will decrease. Of course, very few sensor network environments can be modeled as an isolated wireless environment. For CAFO environments, the main advantage of using wireless sensor networks involves increasing the sampling density and spatial placement in a very congested environment. Considering these conditions, a more involved path loss model is required to understand the electromagnetic environment.

Path losses will occur from many sources within CAFO buildings. There will be natural path loss that can be estimated from Friis’ equation related to the separation distance of the sensor nodes. There will also be path loss caused by signal reflection, multipath reception, signal diffraction, shadowing, and signal
absorption. Friis’ path loss equation can be modified to include these parameters by adding a propagation factor term (Equation 9 and Equation 10).

\[ P_r = G_r G_t \left( \frac{\lambda}{4\pi r} \right)^2 P_i \left| \sum_{i=1}^{n} F_i \right|^2 \]


Where: \( F_i \) = Propagation factor for each path loss element (unitless)

And

\[ F_i = \frac{E_m}{E_o} \]


Where: \( E_m \) = Electric field intensity in the medium (V/m)

\( E_o \) = Electric field intensity in free space (V/m)

When expressed in logarithmic form with unit of decibels, the path loss formula becomes (Equation 11):

\[ P_r = G_r + G_t + P_i - L_o - \sum_{m=1}^{n} L_m \]

Equation 11. Logarithmic representation of modified Friis path loss equation (Derived by Author).
Where: \( L_m \) = Path loss in the medium (unitless)
\( L_o \) = Path loss in free space (unitless)

2.5.2. Previous Research Documentation

With the recent increase in wireless internet applications for both industrial and residential buildings, there has been a sharp increase in research publications dealing with wireless path loss through walls and other obstructions commonly found in the environment surrounding wireless devices. Much of this published research is focused on fully defining the electromagnetic environment in which wireless devices exist in order to better determine the optimal placement of such devices.

Chun-Ming et. al (2005) found that diffraction of wireless signals over metallic objects can be a significant source of path loss within enclosed environments. This work, evaluated path loss within a laboratory environment and considered free space as well as diffraction losses. Diffraction path loss was estimated by using the unitless Fresnel-Kirchhoff Diffraction Parameter. (Equation 12)

\[
\nu = h \sqrt[2]{\frac{2(d_1 + d_2)}{\lambda(d_1 \times d_2)}}
\]

Where.

\[ u = \text{Fresnel-Kirchhoff Diffraction Parameter (unitless)} \]

\[ h = \text{Height of metallic obstruction (m)} \]

\[ d_n = \text{Distance from n node from metallic obstruction (m)} \]

\[ \lambda = \text{Signal wavelength (m)} \]

The path loss response was simulated based on predictive models and experimentally evaluated. Errors were significantly reduced when diffraction was included and the overall error was minimized to less than 2 dB.

In a related study the Fresnel-Kirchhoff Diffraction Parameter was also used to model and verify diffraction path loss through a variety of building materials (Klukas, et al., 2004). This study used the diffraction model and the Fresnel zone parameters to ensure that path loss measurement was directly related to material loss and not artificially enhances by diffraction. Their predictions were confirmed by testing a wireless receiver/transmitter link with a solid aluminum sheet obstructing the line of sight conditions. By testing path loss at distances greater than and less than the theoretical Fresnel zone distance, they confirmed their critical distance calculation. This work was then expanded to calculate attenuation parameters for gyprock, plywood, and cinder block construction materials.

Papadakis et. al (1999) studied the radio propagations of 1.8 GHz signals through a commercial office facility. Unlike many studies that use received reception power as an indicator of path loss, this study used a computer based signal generator and spectrum analyzer to provide highly accurate path loss measurements. The enhanced sampling rate of the spectrum analyzers produced temporal results of signal performance and provided clear insight into short term
variations in path loss and fast fading of wireless signals. Data was collected by establishing a static transmission location within the test building and moving the receiver to a variety of defined measurement points. Fast signal fading was shown to be a major contributor to path loss at very specific locations and could vary by 5-20 dB over short distances. This resulted in high standard deviations of measurement at specific locations ranging from 2.7 – 6 dB. High frequency data was also analyzed to understand the effect of personnel moving in front of the receivers and causing temporary obstructions. It was found that intermediate path loss increases of 10 dB were possible by the short term obstruction of moving people. The single slope path loss model was also applied to predict path loss under specific conditions regarding office door openings, corridor lengths, and floor separations.

Similar work was conducted to focus to again focus on environmental factors that affect path loss of wireless data links (Perez-Vega, et. al, 1997). By using the same modeling form and the same 1.8 GHz frequency band, results showed exponential factors of 2.25 for low human traffic, 2.47 for high traffic, and 2.5 for non-line of sight conditions with variable traffic. Also reported were exponential parameters associated with two comparable buildings. The path loss parameters were found to not be statistically similar between the buildings which stress the theory that only if it is positively determined that the buildings are similar can they be used as inputs into a path loss prediction model. Likewise, fast fading over short distances was again determined to be a highly variable parameter.

Chia-Chin et. al (2005) conducted experiments inside a residential apartment to again evaluate the path loss and signal strength characteristics of the building
materials. A series of tests were conducted to evaluate the effect of transmission frequency on the overall path loss. Significant results showed that for a three bedroom apartment in line of sight conditions, the path loss varied from 10 dB to 27 dB over a range of 3 to 10 GHz. Likewise, a four bedroom apartment in non line of sight conditions revealed similar path loss ranges over the same frequency range, but did exhibit higher levels of variability in signal strength.

Taga et. al (2001) evaluated the impact of close human contact on the gain of an antenna through a series of studies. A Point Measurement Methods was used where an individual holds an antenna stationary in one hand and carries out a series of measurements. The antenna is then moved left and right while staying within the same vertical plane to obtain a mean value. Since this test is carried out with a human holding the antenna, it is necessary to calculate the effect of this interaction to understand the overall performance of the system. Results showed that the human influence on a half wave antenna was a reduction in antenna gain of 2.12 dB.

Akyildiz and Stuntebeck (2006) presented results of wireless network operation in an underground environment. They provided data showing the extreme path loss caused by signal attenuation in soil as well as showing the increase in path loss as the moisture content of the soil increased. They did though provide evidence that wireless networks could be formed in such a harsh environment, but that all link budget parameters including antenna gain and receiver sensitivity must be optimized.
2.6. GAP ANALYSIS

Embedded systems have played a very limited role in real-time evaluation of animal environment parameters. The few systems that have been developed to monitor animal movements or environments are mainly remote data logging systems with little ability to act as a remote decision support system to predict the onset of animal health and environment concerns. Previous work has shown great improvements in sensing capacity when embedded systems are incorporated. The application of embedded systems to CAFO monitoring has the potential to greatly improve the accuracy of measurements and to allow for sensing of environmental parameters that were previously unattainable. Further research is needed to determine the benefits of developing intelligent embedded systems to replace current sensing technology and improve accuracy and sensitivity in CAFO environmental monitoring systems.

Also, analysis of current work in the area of embedded sensor networking for agricultural based operations indicates that limited work is being done with embedded sensor systems and networked systems. Most wired sensor networks discussed in the literature cover only small distances and/or have not been evaluated in the widespread environments seen in large animal production facilities. In order for the successful integration of wired sensor networks into CAFOs, further testing is required to evaluate the data transmission capacity under bus lengths and configurations typically found in CAFOs.

Likewise, the majority of wireless research applications have been focused on embeddable sensors with a proprietary point-to-point wireless communication
system implemented through a commercially available wireless transmitter. While this level of communication can often meet specific research requirements, it is insufficient in the following ways: no expandability without major adjustments to backbone hardware and software, limited robustness and fault protection caused by networking failures, and limited research to address the impact of agricultural environments on wireless transmission capacities.

Furthermore, agricultural systems are often much larger and more dynamic than typically industrial systems such as warehouses, factories, and office buildings. The expansive nature of such systems creates unique challenges with respect to embedded sensor design and networking. Embedded equipment must be able to stand alone as a multi-functional data logger and when necessary, process controller. They must also be interconnected to allow producers and researchers real-time access to data. Previous work has shown that point-to-point wireless systems are inadequate in this application because of high power consumptions rates necessary to broadcast data over the wide coverage area required. In past work, researchers have ignored this limitation and used large battery sources for extended distributed wireless communication. This is unacceptable for some application though, such as animal physiological monitoring where size and battery life are critical parameters in a successful instrumentation design. Advanced mesh networking systems have the potential to solve this research gap by applying a power friendly, expandable, wireless networking system to agricultural applications. Previous work has shown mesh networks to be ideal for industrial applications where similar problems exist, but very little work has analyzed its applicability to agricultural systems. Mesh
networking parameters require additional research though to evaluate the affect of agricultural environment on hop distance and reliability of self configuring systems.

2.6.1. **Ventilation Measurement**

Building ventilation is a fundamental means to control indoor thermal environments and air quality. Sufficient ventilation control of animal buildings is especially important to animal comfort, health and productivity, and energy consumption within concentrated animal feeding operations (CAFOs). Concerns regarding air emissions from CAFOs have grown in recent years. Widespread work by researchers across the continental United States has and continues to be focused on methods to accurately determine pollutant emission baseline measurements as well as mitigation techniques. One component of this current research is the estimation of pollutant emission rates from CAFOs. Emission rates are calculated as the product of the pollutant concentration and the building ventilation rate. Both air pollutant concentration and building ventilation rate are equally important in determining baseline air emission rates for CAFOs and must be measured with high accuracy. However, accurately determining real-time animal building ventilation rates has traditionally been difficult because of the large number of exhaust fans and wide range of installation practices seen in many CAFOs as well as a lack of appropriate monitoring devices.

Building ventilation rate is the sum of airflow rates of each individual building fan operating at any time. Accurately determining the total ventilation rate of a building requires measurement of flow rates of each individual fan. A
A standardized protocol for determining ventilation rate of an agricultural fan is described by ASABE/S565 and ANSI/ASHRAE 51-1999. The BESS Laboratory at the University of Illinois conducts fan tests according to ASABE/S565 and ANSI/ASHRAE 51-1999 to provide unbiased ventilation fan performance data for most commercial agricultural fans. Fan performance data including airflow rates at differing static pressures, fan speed, and fan efficiency are published regularly. Therefore, airflow rates under various static pressure conditions are easily obtained. Research has shown that fans installed at CAFOs are susceptible to dust buildup and loose drive belts. Field installed fans that have been poorly maintained can have airflow rate reductions as much as 67% of its original capacity (Janni et al., 2005). Janni et al. (2005) also found that well maintained fans in situ performance ranged from 20 – 40% lower than BESS Laboratory tests. It was concluded that variations in fan performance were unpredictable and caused by many issues including fan operation and maintenance, shutters design and condition, and precision of installation. Accurate knowledge of fan performance is only possible through field calibration of each fan system.

Simmons et al. (1998) and Gates et al. (2004) have demonstrated a field fan testing system, Fan Assessment Numeration System (FANS), for in situ evaluation of exhaust fan performance for individual fans at animal production facilities. The FANS unit uses a traveling linear array of five anemometers to measure airflow speed at the cross section of a fan for a precise calculation of the fan airflow rate under a range of typical building static differential pressure conditions. The FANS system provided researchers a tool to evaluate fan performance individually in the
field and account for variations between fans. It is not feasible to use a FANS type system to continuously monitor the real-time ventilation rate of multiple agricultural ventilation fans simultaneously due to its cost and complexity.

A general research approach to evaluate ventilation from a production facility is to calibrate each fan’s ventilation rate by conducting multiple FANS fan performance evaluations. The revised fan performance data for each individual fan can then be used to determine the airflow rate of the entire building when coupled with information on the fan operating status and static differential pressure (Wheeler et al., 2002; Darr, 2006). While measurement of static pressure is fairly standardized among various research groups through the application of electronic differential pressure transducers, measurement of individual fan status has been more challenging. Hoff et al. (2004) concluded that it is still a formidable task to accurately determine real-time ventilation rate of an animal housing facility. Therefore, monitoring fan operational status is crucial to determine accurate building ventilation rates.

A variety of methods have been attempted to continuously monitor fan activity (Hoff et al., 2004). These methods aim to measure the cause or derivative activity of a fan’s operation status, such as electric current into the fan motor, fan control relay status, airflow, fan motor rotation, shutter position, and fan vibration. Current transducers and switches have been used to monitor current flow into the fan motor. If current flow is present, it is assumed that the motor is operating (Gay et al., 2006). Split core current monitors are simple and cost effective to install when the motor wiring is exposed. If the motor wiring is encased in conduit, modifications
to the facility must be made to allow for current sensing (Xin et al., 2003). Similarly, monitoring of the fan control relay contacts which drive the ventilation fans has also been used to determine the real-time fan activity level (Ni et al., 2005b). During this study, an open contact relay was supplied with a 5 V signal and the opposite contact terminal was monitored by a data acquisition system. This method has proved to be simple to install, but was dependent on availability of an additional set of contact relays for each fan stage within the production facility. It also had no means to determine if individual fans within a single stage had failed.

A propeller anemometer can be installed in front of an agricultural ventilation fan to determine the magnitude of exhaust (Hoff et al., 2004). These are also subject to mechanical failure caused by dust buildup on the sensor rotational element. Rotational speed sensors attempt to record ventilation rate by measuring the rotation speed of the electric motor which drives the propeller blade (Janni et al., 2005). Typically speed is measured on the electric motor shaft, rather than the propeller shaft. This methodology has the added benefit of being able to determine fan speed, and thus can more accurately calculate the exhaust rate of variable speed fans. Drawbacks to rotational speed monitoring are difficulty in installation and in data acquisition. Many commercial Hall Effect rotational speed sensors require that the sensor be mounted within 12 mm of the metallic element being measured and deviations from this distance can diminish sensing quality. Furthermore, rotational speed sensors output a pulse train signal which has a frequency corresponding to the rotational speed of the measurement device. Few data acquisition systems exist
commercially which will allow for multiple simultaneous measurement of the frequency content.

Sail switches provide a low cost and simple method to indicate fan operational status (Hoff et al. 2004). Sail switches operate as a normally open momentary switch with a large sail wing attached to the switch element. When an airflow condition occurs, the switch is closed and the output signal can be recorded by the data acquisition equipment. Likewise, mechanical shutter switches work in a similar method and change state when a shutter is displaced from its normal zero ventilation position. Using resistive networks, multiple switches can be analyzed by a single analog input channel to reduce data acquisition requirements. However, these sail switches are susceptible to mechanical failure and are sensitive to dust build-up, which could result in non-reliable monitoring.

A vibration sensor method was developed to provide auxiliary fan operational status to the relay contact sensing method and prevent false positive and false negative susceptibility (Ni. et al., 2005a, 2005b). This system utilized a vibration sensor (Catalog No. 49-521A, RadioShack®, Fort Worth, TX) to detect fan activity. Typical agricultural fans produce a mechanical vibration that is transmitted through the fan frame and into the hood which surrounds the fan periphery. Ni et al. (2005a, 2005b) demonstrated the use of a low cost mechanical sensor to detect this vibration signal thus monitor the status of the fan operation. Advantages of detecting hood vibration rather than fan motor vibration include verification that the motor is attached to the fan blade drive shaft and improved safety and ease in installation. It also avoided the false signal in case of a broken fan belt when the
motor was still turning but the fan blade was not. However, it was reported that the sensor is not reliable during long term measurement in harsh environment of animal buildings and a more reliable vibration sensor is needed for fan monitoring at CAFOs (Ni. et al., 2005a, 2005b). Commercial vibration sensors are available from several manufacturers and many are designed to provide an alarm signal when a certain vibration is reached for use in industrial maintenance diagnostics. Several reasons exist why these industrial sensors are not suited for application in agricultural ventilation monitoring including: absence of continuous monitoring capabilities, non-adjustable sensitivity, lack of a digital output signal, or lack of proper housing for release into harsh animal environments.

Furthermore, non-mechanical sensing techniques are also available for ventilation determination within CAFOs. Carbon dioxide ($\text{CO}_2$) is a metabolic product of animals and can be used to estimate ventilation. By monitoring indoor and outdoor concentrations and estimating the animal production rate, model-aided $\text{CO}_2$ balance is another method to calculate ventilation rate in livestock buildings. This method could be applied to both natural and tunnel ventilation buildings. Pedersen et al. (1998) compared the ventilation rates in poultry and livestock buildings with different ventilation systems estimated by using the mass balance method based on animal $\text{CO}_2$, heat, and moisture production. Although good agreements are found between the three methods, only the $\text{CO}_2$ method is recommended for both insulated and non-insulated facilities because of it’s insensitivity to heat transmission loss (Pedersen et al., 1998). Zhang et al. (2005) used this method in estimating gas emission rates from nine naturally ventilated
dairy buildings in Denmark. van’t Klooster and Heitlager (1994) determined the minimum ventilation rate in a swine facility with nature ventilation system using CO₂ mass balance method. The existing research results show that CO₂ balance method is reliable in calculating ventilation rate from animal feeding operations. However, this method is dependent on the accuracy of the model predicting CO₂ production rate of the animals, and can only be applied to those buildings in which the only CO₂ source is the animals (Zhang et al., 2005).

Upon full investigation of previous work in monitoring fan activity for use in determining agricultural fan ventilation rate it was determined that no sensor adequately meets all requirements of determining the on / off status of fans. Further research is required to develop a sensor that can reliably detect fan activity under all environmental conditions including high dust and extreme temperatures, can provide a range of sensitivities and be field adjustable for various sizes and speeds of fans, can be easily installed and will not interfere with the surrounding facilities, and can provide an industry standard digital output signal which will easily interface to commercial data acquisition devices.

2.6.2. DATA ACQUISITION

EPA air emission regulations are backed by limited data sets from agricultural facilities. Further studies are required to fully understand the effect of various production and environmental parameters on air emissions. While analyzers and sensors are available to monitor the key types of air quality parameters (temperature, humidity, carbon dioxide, ammonia, hydrogen sulfide, and
ventilation rate), installation and data collection from these sensors is very difficult and time consuming. Work by Heber et al. (2001) demonstrated a system to collect continuous air quality information in swine buildings. This system employed a central data acquisition location and acquired samples using sampling tubes and electrical wiring. Many of the sample acquisition lines stretched to over 125 m in length. Figure 6 shows a general description of this type of monitoring strategy.

![Figure 6. Traditional measurement methodology for animal production facility.](image)

Installation of a multi-point sampling system as shown in Figure 6 is time consuming and difficult. Extensive labor is required to correctly install the long sampling lines and sensor wiring. Furthermore, a large bank of data acquisition equipment is required to perform sampling of the multiple air environment parameters. In practice, a complete site installation can take over six weeks and countless person hours to complete. The cost and complexity of this type of data collection makes it prohibitive for wide applications.
The measurement methodology depicted in Figure 6 has also been utilized by others researchers interested in air quality monitoring. Continuous monitoring of swine, dairy, and poultry was performed in 2001 using a similar methodology (Schmidt et al., 2002). Furthermore, Whilhelm and McKinney (2001) successfully implemented a similar system for environmental monitoring within swine facilities. One major conclusion made during this work was that buildings which appear structurally similar may be quite different when considering air quality. This uniqueness among CAFO facilities points to a need for a simpler and more efficient system to monitor and evaluate air quality under multiple different environment and structural characteristics.

Alternative studies have focused on short term air quality monitoring with single monitoring points (Redwine et al., 2002; Xin et al., 2003). These studies typically install individual sensors and data acquisition equipment at each sampling location. This adds complexity to data retrieval as each sensor must be downloaded separately and the possibility exists that the data may not be synchronous due to differences in the time stamp reference for each device. While this technique does offer a reduced cost method of measurement, it has been conclusively shown that significant emission rate errors can occur due to insufficient measurement density caused by single point monitoring (Parbst et al., 2000).
CHAPTER 3

METHODS FOR ADVANCED VENTILATION SENSING AND MONITORING

3.1. INTRODUCTION

Calculation of air emission rates is directly based on the product of ventilation rate and exhaust concentrations of a targeted gas, dust, or odor. As such, any errors in the calculation of ventilation rate will add a direct error to the calculation of air emission rate from a livestock facility. Gap analysis of current ventilation methods has revealed a lack of precision in currently available methods for ventilation rate sensing. Embedded sensor technology has the potential to provide improved methods for sensing ventilation. Specific failure modes of previous sensor technology, such as mechanical corrosion, false positive and negative signaling, and sensitivity to the ambient environment, along with difficulty in installation and high data acquisition costs, can all be reduced by embedded sensors which contain no moving parts and can be completely isolated from the harsh, ammonia laden air through appropriate sealing.
3.1.1. Discussion of Staged Ventilation Control

Staged ventilation control has been used in CAFOs for many years to provide a controlled ventilation amount specific to the current internal building environment conditions. Staged systems often mix both proportional and bang-off control systems depending on the cost and complexity of the installations. As the temperature inside a CAFO increases during the warmer diurnal periods, additional ventilation stages are initiated. The magnitude of increase per stage is governed by the animal breeds and quantity housed, individual fan capacity, and total number of controllable fan stages.

The stage controller can be configured as either a computer console which may control multiple buildings simultaneously or a programmable logic (PLC) based system which is dedicated to the environmental control within one specific building. Each of these systems receives temperature information from a single or array of temperature sensors located throughout the CAFO. The intelligent controller will compare the current internal temperature to the desired setpoint and deadband temperatures for each stage. If the temperature is greater than the setpoint plus the deadband for the current highest stage, then the next highest stage is initiated. This increase in ventilation will also cause an increase in static pressure within the building. Static pressure is then also automatically controlled using curtains or other inlet modification systems to change the size of the building air inlet to match the desired pressure setpoint. Due to the high power requirements of ventilation fans, the computer and PLC control systems cannot directly control the operating
function of the fan. Instead, the outputs from the computer based systems are used to drive mechanical relays, which in turn drive the operation of the ventilation fans.

During winter seasons, when ambient air is very cold, it is critical to reduce the ventilation rate so that animals are not exposed to peak low temperatures. It is also important though that enough air is exchanging between the ambient and barn environments so that potentially high levels of gasses do not buildup within the CAFO. This method of providing ventilation to meet minimum air quality standards is termed minimum ventilation and is the lowest form of CAFO ventilation. During minimum stage ventilation the lowest stage fans will run on a specific oscillating cycle. They will maintain this cycle independent of temperature as long as the indoor temperature is below the setpoint. This minimum stage cycle is defined by the CAFO operator and can change throughout the duration of the production season based on animal size and general health. For example, when comparing small to large enclosed animals, it is known that the smaller animals will produce less heat as well as less hazardous gas during their early production period. Based on these known factors it is advantageous to reduce the duty cycle of minimum stage ventilation systems during period when animals are at a very young growth stage. Once the indoor temperature increases above the desired building setpoint, the minimum stage fans will return to normal operation as stage 1 fans. They will turn on or off dependent on the current thermal environment state.

3.2. OBJECTIVES

The objective of this work was to develop a new sensing device to accurately determine the operational status of an agricultural ventilation fan. The sensor must
reliably detect fan activity under all environmental conditions including high dust and extreme temperatures, provide a range of sensitivities and be field adjustable for various sizes and speeds of fans, be easily installed and not interfere with the surrounding facilities, and provide an industry standard digital output signal which will easily interface to commercial data acquisition devices. Furthermore, the sampling intervals used to collect data from ventilation activity sensors will be analyzed and recommendations will be proposed to optimize sampling rates while limited the impact of ventilation errors associated with data sampling.

3.3. METHODS

3.3.1. Energy Model for Ventilation Systems

Commercial CAFO ventilation systems are designed to control both the activity of individual fans as well as the pressure drop across the fan. The pressure drop is automatically controlled by increasing or decreasing the air inlet to a building. The total ventilation is then controlled by turning individual fans on and off. In order to monitor total building ventilation, both parameters must be measured accurately.

Building static pressure and thus the pressure drop across the fans can be accurately measured through a standard pressure transducer. In the majority of CAFO facilities there is little pressure difference between different points along a wall. Fan activity is more difficult to measure both due to its randomness among individual fans and a lack of a standardized measurement method. To identify the optimal sensing point for monitoring fan activity, a thorough understanding of the
energy transfer through a fan system must be known. Each point of energy transfer serves as a point of passive measurement for a monitoring system. By placing the monitoring device further down the stream of energy, the potential for sensing errors is minimized.

The initial energy supply for ventilation fans is provided by the electrical service at the CAFO facility (Figure 7). This energy is distributed to the individual fans when necessary through mechanical control relays. The mechanical relay and the control signal to the relay both constitute viable measurement points. If current is present in the control signal line, then a passive measurement would assume the fan is operational. Likewise, the latching relay element could also be monitored as a passive measurement point. Current flowing out of the control relay then passes through a motor protection circuit such as an arrestor or fuse. Again, current in this path could be monitored as a passive measurement point. It should be noted that any measurement of voltage before the circuit protection element will cause data acquisition errors when the protection circuit is blown. Current that passes through the protection circuit directly enters the fan drive motor, causing a rotation motion. At this stage both the electrical signal and a mechanical rotation signal could both constitute passive measurement locations. Furthermore, as a byproduct of the mechanical rotation, the motor will also put off a heat loss associated with its own inefficiencies. This heat loss is another path of passive activity measurement.
The rotating motor drives a belt transmission during the next stage of energy transfer. The belt transmission allows for a speed reduction ratio between the motor and fan blade. It also acts as a torque amplifier to lower the startup torque requirements of the motor. The energy received into the belt transmission is the difference between the motor output power and any power loss through inefficiency. A measurement of mechanical belt drive speed would provide a sensible location for a passive airflow sensor. The next to last stage in energy transfer is to convert the mechanical rotation of the belt drive system into the fan blade. This provides another location to insert a mechanical sensing element to monitor the rotation of
the fan blade directly. The final stage of energy transfer is the conversion of a mechanical rotation into airflow. This step is accomplished through the specific design of the fan blade, but does also have a path of inefficiency where energy is lost. All energy directed into the fan blade will be converted into either airflow or losses which result in the mechanical vibration of the fan enclosure. The airflow path is a fluid medium and is difficult and expensive to measure on a fan by fan basis. The inefficiency measurement point though can be quite direct to measure through a properly selected accelerometer. This method of sensing can be considered an active sensor even though it does not measure airflow directly, because it is located at the final stage of energy transfer (Table 2). If airflow is present, inefficiencies and thus vibration will also be present. If airflow is not present either from an off control signal or other energy transfer failure, then vibration will also not be present.
<table>
<thead>
<tr>
<th>Location</th>
<th>Measurement Method</th>
<th>Measurement Type</th>
<th>Stage Number from Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow</td>
<td>Anemometer</td>
<td>Active</td>
<td>0</td>
</tr>
<tr>
<td>Vibration</td>
<td>Accelerometer</td>
<td>Active</td>
<td>0</td>
</tr>
<tr>
<td>Fan Driven Pulley</td>
<td>Mechanical Speed Sensor</td>
<td>Passive</td>
<td>1</td>
</tr>
<tr>
<td>Motor Drive Pulley</td>
<td>Mechanical Speed Sensor</td>
<td>Passive</td>
<td>2</td>
</tr>
<tr>
<td>Motor Power Input</td>
<td>Current Sensor</td>
<td>Passive</td>
<td>3</td>
</tr>
<tr>
<td>Motor Heat Loss</td>
<td>Temperature Sensor</td>
<td>Passive</td>
<td>3</td>
</tr>
<tr>
<td>Circuit Protection</td>
<td>Current Sensor</td>
<td>Passive</td>
<td>4</td>
</tr>
<tr>
<td>Control Relay Latch</td>
<td>Mechanical Position Sensor</td>
<td>Passive</td>
<td>5</td>
</tr>
<tr>
<td>Input Control Signal</td>
<td>Current/Voltage Sensor</td>
<td>Passive</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2. Comparison of techniques for measuring airflow from agricultural ventilation fans.

3.3.2. *Design Criteria for Embedded Ventilation Monitoring Sensor*

The above description of passive and active ventilation monitoring methods indicates many potential sources of monitoring points. Since the desire of research applications is to maximize the accuracy of measurement, it is desirable to focus on methods with the least potential for errors and those which provide the most active measurement of the desired parameter. Direct airflow measurement, while commercially available, is not economically viable given the hundreds of fans per barn that require monitoring. Thus the most desirable choice for ventilation monitoring was to detect the presence of vibration along the fan hood during motor operation. An embeddable accelerometer was used to detect the presence of
vibration and a signal conditioning circuit was used to convert the vibration signal into a purely digital signal. The digital output was compatible with TTL signal levels.

3.3.3. **Accelerometer Selection**

An accelerometer was used to measure the magnitude of vibration present on the fan hood (ADXL320, Analog Devices®, Norwood, MA). The accelerometer utilizes MEMS technology to provide a ±5g, 2-axis accelerometer along with signal amplification into a 4 mm wide by 4 mm long by 1.4 mm tall package. The accelerometer can be mounted directly to a custom printed circuit board through its 16 pin Lead Frame Chip Scale Package (LFCSP). This integrated sensor and signal amplifier provided a sensitivity of 312 mV/g when powered by a 5 V power supply. An external capacitor was installed to set the maximum sensor bandwidth. The maximum expected vibration frequency was calculated based on a 3600 rpm fan with a 6 blade propeller, which would produce a vibration frequency of 360 Hz. A 0.01 μF capacitor was used to limit the sensor bandwidth to 500 Hz.

3.3.4. **Signal Conditioning Design**

The objective of the analog circuit design was to convert the oscillatory vibration signal into a clean digital signal that could be easily recognized with standard digital input data acquisition equipment. Testing of the ADXL320 accelerometer showed that when powered by a 5 V supply, the output under 0 g was 2.5 V. The output voltage would stray from this level based on specified sensor
sensitivity of 312 mV/g. Laboratory testing of a 61 cm agricultural fan showed maximum accelerations from 1.5 – 2 g depending on the placement of the sensor.

An analog circuit was designed that would condition the raw analog acceleration signal under the following process (Figure 8):

- Decouple the sinusoidal acceleration signal to remove steady state offset,
- Rectify the signal to enhance signal strength,
- Filter the rectified signal to create a steady DC signal,
- Amplify the filtered DC signal,
- Provide a means to adjust the amplification level to exceed the positive threshold for the Schmitt trigger circuit,
- Create a digital signal with hysteresis by passing the amplified signal through a double Schmitt trigger.
Figure 8. Simulation of vibration sensor signal output from initial motor activation ($t_0$) to full speed fan operation ($t_1$).

The raw accelerometer signal was decoupled by passing the signal through a 1 $\mu$F electrolytic capacitor. A diode array was used to rectify the signal, which enhanced the overall content of the signal. The rectified signal was smoothed using a simple Resistor-Capacitor filter to remove the signal ripples. Values of 5.6 kΩ and
0.1 μF were used for the RC circuit \( (f_c = 285\, Hz) \). A 560 kΩ resistor was also placed in parallel across the capacitor to help drain the signal to ground when no oscillations were present. This helped to prevent voltage buildup within the capacitor.

After passing through the RC filter circuit, the sensor signal was a very low DC voltage. When exposed to vibration from a fan hood, the sensor would output a higher voltage signal on the magnitude of a few tenths of a volt depending on the fan size and speed. This signal was too small for standard digital input devices to recognize, so an appropriate amplification circuit was designed. An operational amplifier (MAX495, Maxim Integrated Products®, Sunnyvale, CA) with rail-to-rail and low voltage single power supply operation was chosen for this design. Because fans with different sizes and installation methods produce hood vibrations with different magnitudes, the gain on the operational amplifier was designed to be field adjustable. This was accomplished by using a potentiometer as the gain resistor in the non-inverting amplifier circuit.

The feedback resistor \( R_{fb} \) was set at 10 kΩ and a 10 kΩ potentiometer was used for \( R_{gain} \). By adjusting the potentiometer resistance from 10 kΩ to 2 Ω, a circuit gain from 2 to 5000 was achieved. No conditions were identified where a gain of 2 exceeded that necessary for proper circuit operation.

Under normal operating conditions using a 61 cm agricultural fan with a 61 cm fan hood and running at 1075 rpm the sensor gain could be tuned to provide a 0.6 V signal when the fan is not operating and a 4.8 V signal when the fan is operating. This is sufficient for the majority of TTL digital input data acquisition
systems commercially available, but given the unknown environment of future installations a Schmitt trigger circuit was added (SN74LVC2G14, Texas Instruments®, Dallas, TX). The Schmitt trigger circuit is an inverter circuit which has different voltage thresholds for positive going and negative going signals. A dual trigger was used to correct the inverting logic of the initial trigger so that a positive trigger output would correspond to the fan motor being turned on. This integrated circuit provided a hysteresis of 1 V between a positive going threshold of 3 V and a negative going threshold of 2 V.

In addition to the Schmitt trigger output signal being transmitted to the appropriate data acquisition equipment, the signal was also used to activate a light emitting diode (LED) located on the sensor body. This allowed for troubleshooting during sensor installation, as the installer can reference the LED to determine if additional gain adjustment is necessary.

3.3.5. **SENSOR PACKAGING**

The circuit components were installed on a printed circuit board with final overall dimensions of 4.7 cm long and 1.0 cm wide. The completed board was installed within a plastic potting box with final overall dimensions of 5.0 cm long and 1.3 cm wide (Figure 9). Five wires extended out of the box 30 cm and were mated with a three wire and a two wire quick connect harness. The three wire connector provided connection to the sensor power supply as well as the Schmitt trigger signal output. The two wire connector was an auxiliary connection used to measure the operational amplifier output. This was used to expedite installation
time by allowing the installer to set the operational amplifier output at a recommended level before performing minor gain adjustments with the fan motor running.

To prevent sensor deterioration caused by moisture and corrosion, a potting compound was used to seal the circuit board and components from the external environment. Careful selection of the potting compound was necessary to ensure that proper thermal and electrical properties were maintained and that the epoxy would harden rigidly. A soft silicone-type potting compound would not work because it would act as a dampener and reduce the effective vibration signal which reaches the sensor board. A hard epoxy based potting compound (832B, MG Chemicals®, Surrey, B.C., Canada) was used for this project and testing showed that the sensor operation was not affected by the potting material.

A hole was drilled through the enclosure and potting compound after the epoxy had hardened to allow a #6-32 machine screw to pass through. This screw was used to fasten the sensor directly to the fan hood.
3.3.6. **SENSOR INSTALLATION TO THE VIBRATION SOURCE**

The sensor must be rigidly mounted directly to the fan hood or other mounting point that transfers the mechanical vibration created by the rotating fan propeller. The mechanical fastening is accomplished through the #6-32 machine screw that passes through the sensor potting compound. A single 0.35 cm diameter hole must be drilled in the fan hood to allow for the sensor mounting. The use of other soft joint fasteners such as self tapping screws are not feasible, because they will loosen over extended exposure to vibration. Although the exact mounting location is not critical because of the threshold adjustment of the sensor, it is suggested that the sensor be placed at the location which exhibits the highest level of vibration.

Based on the design and configuration of the sensing element, the output signal is insensitive to the sensor orientation. Figure 10 shows an example of how
the vibration sensor is typically mounted. Only the Y axis is sensitive to vibration, thus the X-Z plane should be mounted directly to the fan hood surface (Figure 10). Any vibrations along the hood would then be in the Y direction and will be recognizable by the sensor.

Figure 10. Typical mounting of the vibration sensor on the fan hood, nearest the greatest vibration source.
3.4. RESULTS AND DISCUSSION

3.4.1. ANALOG MEMS VENTILATION MONITORING

VALIDATION OF SENSOR PERFORMANCE

To test the cyclic response of the sensor over an extended time period a simulated fan vibration system was used. A standard 227 L, 16.99 m³/h air compressor that vibrated at a similar magnitude (±1 g) and frequency (60 Hz) to a standard agricultural fan was used as the vibration source for the test. The compressed air was exhausted at a constant rate after its pressure was reduced by a pressure regulator. A pressure transducer continuously recorded the regulator’s outlet pressure, which fluctuated as a function of the pressure in the 227 L compressor cylinder. The new sensor was installed on the compressor body. The signals of the pressure transducer and the vibration sensor were sampled every second, averaged every 15 s, and recorded in a data file for comparison. The 15 s averaging cycle was a common practice for recording CAFO emission data and was thus used as a standard of evaluation during the initial test procedures.

Figure 11 presents comparison of two sensor signals during compressor operation when the compressor was turned on for 1 min and cycled every 6 min. The manifold air pressure, which was downstream from the compressor tank and a pressure regulation valve, was monitored by an electronic pressure transducer. Based on the operating characteristics of the pressure regulation valve, when the compressor was turned on the manifold pressure would decrease. When the
compressor was cycled off, the manifold pressure would slowly increase. The results of the vibration sensor were compared to the compressor manifold pressure after a 14 day testing period. The vibration sensor output had a 100% correlation to the manifold pressure signal, indicating that each time the manifold pressure decreased, the vibration signal indicated an active state. Furthermore, during the 14 day testing period, no false positive output signals were recorded by the vibration sensor.

Figure 11. Comparison of vibration sensor performance to pressure fluctuations in the manifold pressure of a compressor which simulates fan vibration.
**EFFECT OF DISENGAGED PROPELLER**

Testing was conducted to evaluate the effect of a disengaged propeller on the vibration sensor performance. Disengaged propellers are a common problem when belt driven fan systems are poorly maintained and the drive belt becomes loose or disconnected. A 61 cm diameter agricultural fan (Model AT24Z, Aerotech, Mason, MI) was used to test the response of the vibration sensor under both engaged and disengaged propeller conditions. Five sensors were tested individually. A programmable logic controller (PLC) was used to turn the fan on for a 30 second period and then turn the fan off for a 30 second period. The status of the motor control signal as well as the vibration sensor output signal was recorded continuously on 0.5 second intervals. Tests were conducted individually for engaged and disengaged propeller conditions. The length of test was manually controlled, thus the overall number of fan cycles varies among tests.

Results of propeller tests revealed that when properly adjusted, the vibration sensor will not trigger false positive readings when vibration is present from a motor, but no propeller is present (Table 3). This is due to a higher magnitude of vibration being induced by the propeller mass as opposed to motor only systems.
Table 3. Sensor response to fan testing with a disengaged propeller.

**Effect of Freewheeling Propeller**

Freewheeling propellers are common on CAFO fans when an external wind source is present. When this wind blows directly into a fan, the propeller blade can begin to rotate which causes false positive fan activity readings with rotational and anemometer type monitors. To verify the response of this vibration sensor to freewheeling propellers, a simulated high wind environment was created within a testing laboratory. A vibration sensor was attached to the hood of a 61 cm agricultural fan and the sensitivity was adjusted to the normal operating conditions. An additional fan was placed directly inline and 1 m away from the test fan and was used to simulate a direct wind source. The wind simulator fan was able to produce a wind load of 16 km/h on the test fan. Again, a PLC was used to cycle the simulated wind source on and off at 30 sec intervals. Three separate vibration sensors were tested continuously, each over a period of 4 h. Each sensor was subjected to 240 cycles of wind load activity. Over the duration of the test, zero false positive readings were recorded by the vibration sensors. Although the fan propeller did rotate due to

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Propeller Status</th>
<th>Number of Fan Cycles</th>
<th>Recorded On Events</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Engaged</td>
<td>1459</td>
<td>1459</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>Disengaged</td>
<td>1206</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>2</td>
<td>Engaged</td>
<td>1470</td>
<td>1470</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>Disengaged</td>
<td>1398</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>3</td>
<td>Engaged</td>
<td>1872</td>
<td>1872</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>Disengaged</td>
<td>1507</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>4</td>
<td>Engaged</td>
<td>1437</td>
<td>1437</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>Disengaged</td>
<td>1448</td>
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<td>0.2%</td>
</tr>
<tr>
<td>5</td>
<td>Engaged</td>
<td>1339</td>
<td>1339</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>Disengaged</td>
<td>1168</td>
<td>39</td>
<td>3.3%</td>
</tr>
</tbody>
</table>
the wind load, the speed of rotation and thus the amount of vibration generated was not sufficient to switch the logic level of the sensor.

**EFFECT OF AMBIENT CONDITIONS ON SENSOR PERFORMANCE**

Typical installation on external agricultural fans required the sensor to withstand temperature variations from peak summer temperatures to minimum winter temperatures. It must also withstand weather events such as rain and snow. To test the design integrity against such harsh environmental conditions five sensors were placed in a water bath at a depth of 1 m. After a 168 h period, the sensors were removed from the bath and tested again on a 61 cm agricultural fan. The response for each sensor was identical to the response prior to immersion in the water bath, indicating that the potting compound was sufficient to seal the sensor from the corrosive effect of moisture.

To simulate changes in the ambient temperature, three sensors were placed in a 0°C freezer for a 72 h period. The sensors were then removed from the freezer and immediately installed on a fan located in a temperature controlled research laboratory. The ambient room temperature was 27°C and the response of the sensor was measured as its internal temperature warmed from 0°C to 27°C. Sensor response data along with internal sensor temperature data were collected and a regression analysis was conducted to evaluate the effect of temperature change on the sensitivity of the device. A thermocouple was embedded in the potting compound of each sensor during construction with the leads protruding from the sensor enclosure. This allowed the internal temperature to be monitored while the sensors...
warmed back up to room temperature. The amplitude gain of the sensor was monitored versus the core temperature of the device. Amplitude gain was calculated as the ratio of output voltage under a vibration situation to the output voltage when no vibration was present. The operational amplifier gain and the vibration magnitude were maintained constant throughout the testing period. Two hundred and sixteen observations of temperature versus amplitude gain were recorded for all three sensors.

Figure 12 shows the results of the regression analysis concerning the influence of temperature on the amplitude gain of the activity sensors. While the regression line indicated that there is a slightly negative linear relationship between the temperature of the sensors and the amplitude gain of the sensors, further analysis shows this to be statistically insignificant based on a p-value of 0.172 for the slope of the regression line. The regression plot does show a substantial amount of variance in the amplitude gain, especially at lower temperatures where the difference between the maximum and minimum amplitude gains for a steady temperature were as high as 10%. The Schmitt trigger circuit will prevent these slight fluctuations in amplitude gain from posing any negative effect on the operation of the sensor by providing a band of effective operation. When considering each sensor response individually, the influence of temperature is also statistically insignificant with p-values of 0.179, 0.287, and 0.760, respectively.
Regression Analysis: Amplitude Gain versus Sensor Temperature (°C)

The regression equation is:  
\[
\text{Amplitude Gain} = 54.7 - 0.0236 \times \text{Sensor Temperature (C)}
\]

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>54.6619</td>
<td>0.3269</td>
<td>167.23</td>
<td>0.000</td>
</tr>
</tbody>
</table>

S = 1.54825  
R-Sq = 0.9%  
R-Sq(adj) = 0.4%

Figure 12. Regression analysis of sensor amplitude gain versus sensor internal temperature.
**EFFECT OF FAN SPEED ON SENSOR PERFORMANCE**

Variable speed fan motors are often used to create a variable ventilation rate from agricultural fans. When the speed of a fan decreases, so does the frequency at which the hood vibrates. To test the effect of fan speed on the sensor performance, the sensor was attached to the hood of a variable speed 61 cm agricultural fan. The fan speed was adjusted from 488 to 1075 rpm. The measured parameter was the filtered analog output signal with the amplifier gain set at 26.2. For all ventilation rates tested, the sensor provided an analog output of 5.01 V, indicating that the operational amplifier output was saturated (Table 4). This condition was well above the positive going threshold of the Schmitt Trigger circuit, thus the digital output was high indicating that the fan was running. As a result, the sensor can accurately determine the operational status of variable speed fans, but will not provide a varying voltage output proportional to fan speed.

<table>
<thead>
<tr>
<th>Fan Speed (rpm)</th>
<th>Analog Output (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>488</td>
<td>5.01</td>
</tr>
<tr>
<td>641</td>
<td>5.01</td>
</tr>
<tr>
<td>768</td>
<td>5.01</td>
</tr>
<tr>
<td>895</td>
<td>5.01</td>
</tr>
<tr>
<td>1056</td>
<td>5.01</td>
</tr>
<tr>
<td>1075</td>
<td>5.01</td>
</tr>
</tbody>
</table>

Table 4. Vibration sensor output over a range of fan rotational speeds.
FIELD EVALUATIONS OF THE VIBRATION SENSOR

Field testing of the vibration sensor was conducted at a poultry layer facility housing approximately 170,000 hens. Vibration sensors were connected to 3 fans representing stages 1, 4, and 5 of the ventilation system. Simultaneous fan stage monitoring was also recorded through direct monitoring of the fan control relays. On each of the fan control relays for stages 1, 4, and 5, a 5 V signal was applied to an extra relay contact. The feedback from this relay contact was then recorded as an indication of true fan status (Hoff et al., 2004). Continuous data were collected for 7 days and analyzed to determine the correlation between the new vibration sensor and the fan relay monitoring method. The vibration sensors were sampled and recorded 6 times per minute, while the fan control relay signals were sampled 4 times per minute. The data were classified into 1 min intervals to reduce the influence of temporal effects associated with the different sampling intervals. Each 1 min interval was evaluated individually, with a threshold of 50% set to indicate an active fan for that particular monitoring interval. For the vibration sensors, sampled at 6 times per minute, if at least 3 data points per minute reported an active fan state then the 1 minute fan data was classified as active. Likewise, for the fan relay monitor, it was required that at least 2 samples reported an active status in order for the 1 minute data to be classified as an active fan state. The data from each sensor was then compared for each 1 minute sampling interval. Stage 1 fans remained active over the entire duration of the test and weren't used for comparison purposes. For Stage 4 fans, the vibration sensor method calculated a total on-time of 148.9 h as compared to 149.15 h for the relay monitors. This resulted in a 0.17%
underestimate of ventilation. For Stage 5 fans, the vibration sensor method calculated a total on-time of 107.6 h as compared to 106.75 h for the relay monitors. Again, the vibration sensors underestimated ventilation of this stage by 0.79%. This deviation can be explained by the operating principles of the two methods being compared. The vibration sensors measure fan activity only once the fan motor is running at a speed where airflow is present. The relay monitors on the other hand, assume airflow to occur as soon as power is applied to the fan motor. This will lead to indication of fan activity before the fan reaches full speed and thus will create longer activity times (Figure 13).
Figure 13. Comparison of fan pressure drop to active vibration sensing and passive relay monitoring of ventilation status.

A six month full scale effectiveness test was also performed at a 1000 head swine finishing facility, which was outfitted with a six stage fan control system. The test was conducted from December 2005 to May 2006. There were a total of six fans to provide tunnel ventilation in this facility and were each independently controlled by an electronic control system (AeroSpeed 2.4, Aerotech, Mason, MI). The vibration sensors were fixed directly to the fans via the mounting screw and were again placed very near the propeller periphery where the largest magnitude of vibration was
found. The vibration sensor data was used to calculate the ventilation rate of the building when coupled with pressure drop information for each fan (Figure 14).

![Graph of ventilation rate and temperature over time](image)

Figure 14. Fan activity summary from 1000 head swine finishing facility. May 2006.

The beginning of this study coincided with the placement of 1000 new animals with an average weight of 19.2 kg per animal. Also, during the first month of the study (December 2005), the average ambient temperature was 2.6°C with an average maximum daily ambient temperature of 7.6°C. The combination of small animal weights and low ambient temperatures caused the ventilation system to run in minimum operation mode during the entire month of December 2005. During this period, a total of 1901 minimum stage ventilation cycles were monitored by the
data acquisition equipment. Also during this period, no positive readings were present from any other vibration sensors attached to adjacent fans. This was an indication that the vibration developed by a single fan will be dampened through the building to a reduced magnitude that will not trigger false readings on adjacent fans.

3.4.2. **DIGITAL iMEMS VENTILATION MONITORING**

The analog vibration sensor was limited by its inability to adapt its filtering protocol based on the environmental needs of a particular CAFO. For example, the threshold level was very difficult to set correctly when the sensor was installed on a fan with a low vibration footprint and directly adjacent to a fan with a high vibration footprint. These differences in vibration magnitude per fan are commonly caused by poor fan maintenance. In this situation, the frequency imposed by the adjacent fan could be very close in magnitude to the frequency of the desired fan. Furthermore, the analog sensor design provide no method to filter out short term signals which could be caused by wind gusts, servicing, or other unknown impetus. The desire to improve these characteristics as well as create a sensor that will be adaptable to future projects let to a new design which utilizes digital microcontroller electronics to monitor the analog vibration signal and then determines the fan status through a programmable algorithm.

The basic vibration sensing circuit was maintained during the redesign process. An ADXL accelerometer was still used to sense the magnitude of vibration. The remaining analog circuit was replaced with a PIC16F684 microcontroller produced by Microchip (Figure 15). The analog vibration signal from the
accelerometer was read directly by the microcontroller's analog to digital converter and a software program was written in PIC Basic Pro (Melabs Inc.) to decipher the signal content.

Figure 15. Digital vibration sensor circuit diagram. Schematic created in Altium Design Explorer, 2002 with manufacturing outsourced to Advanced Circuits, CO.

The microcontroller continuously ran the programmed software and provided digital outputs to the data acquisition system when the fan was active. An LED was also activated during the period of active ventilation. The operational procedure of the microcontroller program can be described as:

- Assign and initialize variables
- Initialize control registers
• Operate main sampling loop
  o Continuously sample vibration signal for 1 second duration
  o Calculate vibration signal parameters
    ▪ Maximum vibration magnitude
    ▪ Minimum vibration magnitude
    ▪ Range of vibration
    ▪ Average vibration frequency
  o Apply sampling filters and protocol
  o Determine fan activity
  o Assert fan activity to digital output and LED indicator
  o Report fan parameters to auxiliary data logger via serial port

Full program code is available from the Appendix.

During the 1 second reporting interval, vibration sensor will be sampled at a rate of 5000 Hz to ensure all minimum and maximum values are acquired. Maximum and minimum values were updated continuously during this sampling period to improve processing efficiency. The range of vibration was calculated as the difference between the maximum and minimum vibration values for a given sampling period. The vibration frequency was calculated by continuously calculating the average vibration magnitude, then monitoring the number of crossover points for which the current vibration output varied around this average.

A series of tests were conducted to understand the temporal changes in vibration magnitude. A preliminary study recorded the vibration magnitude in units of digital counts at one second intervals for a particular 48 inch exhaust fan. The
plotted results clearly show the sensors ability to recognize differences in fan activity status. The majority of sampling points while the fan is running report a vibration magnitude of greater than 175 counts (Figure 16). The value of counts was calculated as the difference between the maximum and minimum count values directly acquired from the analog to digital converter in the microcontroller. When an analog to digital conversion was processed the analog value ranging from zero to five volts was digitized over a range of 0 – 255 counts. Thus the 175 count value represents a range of ±87 counts or ±1.7 volts. The ADXL 322 accelerometer provided a sensitivity of 750 mV/g with a 5 volt supply, indicating that the acceleration measured was approximately 2.25 gs. This was in excess of the ±2g sensor specification and indicates that the sensor was saturated during this measurement. Over a 7 day study of this particular fan, the average on-time vibration magnitude was 194 counts. For this particular fan, an accurate vibration magnitude threshold could be set at any value from 35 to 150 counts.
Figure 16. Example vibration output from the digital sensor showing differences in output magnitude between the fan inactive and fan active states. Output units are raw count values from the 0 – 5 V FSR, 8 bit analog-to-digital converter.

During the 7 day study of this particular fan, a total of 456 on-off cycles occurred. A histogram of the vibration magnitude data shows three unique lobes (Figure 17). The lowest magnitude lobe represents periods when no fans are running. The second lobe results from an immediately adjacent fan running while the fan of interest was still turned off. *This shows that the adjacent fans do in fact increase the vibration signal of nearby fans.* The third and largest lobe represents the vibration signal when the fan of interest was running. Infrequent data that falls between lobes two and three represent the startup and shutdown phase of the fan.
A vibration magnitude of 35 was chosen to represent the running status of the fan. This will not only capture the entire upper lobe, but will also capture the majority of starting and stopping operations. The result was a very accurate estimation of total airflow. A validation test was performed to determine the suitability of the 35 magnitude threshold. The raw data was reprocessed to find any data spike in which the magnitude 35 threshold produced a fan on-time event which was shorter than one minute in duration. The results of this analysis revealed a
minimum on-time of 80 seconds, thus verifying the reliability of the magnitude 35
count threshold.

A secondary analysis was conducted based on simultaneous data collected
from both a digital vibration sensor and a rotary speed sensor. The speed sensors
were used to measure the rotational speed of the propeller blade, thus provide a
true comparison for fan operation. The vibration data was divided into two subsets
using a rotational speed of 10 rpms as the criteria for division. With a maximum
speed of 70 rpms, this threshold is very near the lower boundary of operation and
should be adequate to capture startup and shutdown events.

A histogram plot of only the data points validated as occurring during fan
operation is shown (Figure 18). Agreeing with past results, the vast majority of data
points are above the 35 count magnitude threshold. The points below the threshold
represent 0.62% of the points and can be declared as outliers. One explanation of
these results was that the sampling of fan speed and vibration was not
simultaneous. The data logger first measured the vibration magnitude, then the fan
pulses. It was possible to measure the vibration before the fan startup and still
record an active fan from the rotational speed sensor.
The test fan was monitored continuously over a six week period. During the duration of the study, a rotational speed sensor was used to validate the sensor performance. The time series plot below, showing a summarized 15 minute sampling interval of the fans, reveals that a shift in the output acceleration magnitude occurred during the later phase of the study (Figure 19). This shift coincides with the failure of a voltage regulator used to supply power to the sensor. The results though show that even with a reduced input voltage, the digital sensor
can still decipher the difference between an active and inactive fan. This is in stark contrast to the analog vibration sensor.

![Figure 19. Continuous vibration magnitude for single fan monitored with a digital sensor. A power supply failure occurred on May 14, 2007.](image)

A summary of the digital sensor results yield a significant improvement in sensor technology over the previous analog sensor method. The field programmability and internal computing power of the digital sensor provide flexibility in adaptation of future sampling algorithms and allow for the potential of adaptive filtering and maintenance prediction alarms to be incorporated. When
compared to other common ventilation monitoring sensors, the digital vibration sensor also provides a significant increase in both installation ease and long term reliability.

The sensitivity of sensors is often directly related to the input voltage supply of the system. This digital sensor was specifically designed to function independently of the supply voltage and to minimize current draw which induces excessive supply voltage drop. Due to the size of CAFO facilities, vibration sensors are often linked with a common power supply bus to reduce the number of wires required during installation. In doing so, the cumulative current of all the sensors must travel through the same power supply line and thus the voltage drop through the line is increased. Voltage regulation at the sensor was considered during the design phase of the digital sensor, but because this also induces increased current draw it was decided that no voltage regulation would be included. Instead the sensor was designed to operate from a supply voltage ranging from three to five volts.

The output sensitivity of the iMEMS accelerometer was linearly related to the supply voltage by (Equation 13):

\[ g = \frac{140 \text{ mV}}{V_{ss}} \]

Equation 13. Accelerometer sensitivity (Derived by Author).

Where: \( V_{ss} = \text{Accelerometer supply voltage} \)
Likewise the analog to digital converter of the 16F684 microcontroller was related to the supply voltage by (Equation 14):

\[
\text{Counts} = 3.9 \text{ mV} / V_{ss}
\]

\[\text{Equation 14. Microcontroller sensitivity (Derived by Author).}\]

Where: \(V_{ss}\) = Microcontroller supply voltage

This design then allowed the ratio between analog-to-digital conversion counts and output sensitivity to maintain constant over the desired operating range (Equation 15).

\[
\text{Sensitivity} = \frac{g}{\text{counts}} = \frac{V_{ss} \times g}{140 \text{ mV} / \text{count} \times V_{ss} / 3.9 \text{ mV}} = 0.0278 \frac{g}{\text{counts}}
\]

\[\text{Equation 15. Digital vibration sensor sensitivity (Derived by Author).}\]

A series of tests were conducted to experimentally verify this linearity over a range of supply voltages (Figure 20). A digital sensor was attached to a running 24" agricultural fan. The fan speed was adjusted to simulate different vibration magnitudes. For each fan speed, the magnitude of vibration was measured by logging the result of the ADC directly to a computer data file. This was accomplished by utilizing an auxiliary serial communication port on a specially programmed sensor. The three fan speeds tested were 1075, 895, and 768 rpms. A slight linear trend is present in the regression analysis of each treatment, but the effect of this does not provide a major impact to the sensor operation. At full, medium, and low
speeds, the slope of the regression lines were 4.23, 1.13, and 5.53 respectively. For full certainty in the operation of the sensors over a wide operating voltage and a wide fan speed range, a minimum deadband of 10 counts must be maintained between the on and off states of the fan.

Figure 20. Comparison of vibration magnitude from the digital vibration sensor to power supply voltage for three typical fan speeds.
3.4.3. **Measurement Errors Associated with Ventilation Monitoring**

Monitoring the activity status of all ventilation fans was only one factor in accurately measuring the ventilation rate from a CAFO. Significant measurement errors can be induced by neglecting to sample the fan activity monitors at a sufficient frequency. This was especially significant during minimum ventilation states where it is common for a single fan to cycle on for as quickly as 30 seconds, then cycle off for several minutes. Sampling intervals must always be less than the shortest on-time of the system to ensure that active fan events will not be missed. The single point error associated with ventilation monitoring will also be directly proportional to the width of the sampling interval, with a maximum error of one sampling interval. An illustration of this concept can be considered for a 30 second minimum stage on-time with a 30 seconds sampling interval (Figure 21). It is possible that the data acquisition system would sample the fan status on the instance the fan started and also 30 seconds later on the instance before the fan stopped. The data acquisition system would record 60 seconds of fan activity time and thus induce a 100% ventilation measurement error for a single point measurement. As the duration of the ventilation monitoring period increases, so does the accuracy of the overall ventilation measurement. Based on the Central Limit Theorem, the summation of a random variable with a finite variance, such as fan activity, will be approximately normally distributed. As the number of samples in this distribution increases, the statistical confidence in estimating the distribution mean, or in this case the true ventilation rate, increases.
Figure 21. Illustration of measurement errors caused by sampling intervals.

Data acquisition for ventilation monitoring was quite different than typical analog data acquisition in that the signal of interest was a piecewise, discrete, and random function. Automated ventilation controllers precisely controlled the airflow through a CAFO facility by turning individual fans on or off until the airflow was sufficient to cool the internal building environment. Often, stage control was used, where fans were grouped divided into several groups and stages fans turned on simultaneously when additional airflow was required. Errors occurred in monitoring total airflow rate when the on time of each fan was not properly acquired. The emission load for a particular barn was directly calculated from the airflow and gas concentration, thus any error in airflow measurement would directly impact the quality of the emission calculation (Equation 16).
\[ E_i = Q_{air} \times (C_{i,\text{exhaust}} - C_{i,\text{inlet}}) \]


Where: 

- \( E_i \) = emission rate for gas (lbs/day)
- \( Q_{air} \) = building air exchange rate (cfm/day)
- \( C_{i,\text{exhaust}} \) = concentration of gas in the outlet (lbs/cfm)
- \( C_{i,\text{inlet}} \) = concentration of gas in the inlet (lbs/cfm)

Many commercial data loggers used for CAFO air quality baseline studies were limited in their data storage capacity. As sampling rates increased, the frequency of research personnel traveling to the research site to download data also increased. Optimization of the sampling rate will result in the fewest number of investigator trips to the research site while ensuring the high quality of the collected data. Furthermore, for large baseline environment studies, the quantity of data collected can be on the order of 10’s of megabytes per day. By optimizing the sampling frequency even when high frequency collection was possible, data storage and processing requirements will be minimized.

The instantaneous error rate associated with improper ventilation rate sampling will vary depending on the stage of ventilation control currently used. Sampling errors will thus only be associated with this highest active stage of ventilation (Equation 17).
Equation 17. Emission estimation error based on measurement of ventilation stage ontime (Derived by Author).

\[
\% \text{ Error} = \frac{\text{Measured Ventilation}}{\text{True Ventilation}} = \frac{S_{1m} + S_{2m} + S_{3m} + \ldots + S_{nm}}{S_{1t} + S_{2t} + S_{3t} + \ldots + S_{nt}}
\]

Where:  
\( S_{nm} = \) Measured ontime of \( n \) stage fan  
\( S_{nt} = \) True ontime of \( n \) stage fan

This error representation shows that higher error percentages will occur during lower fan stages. Errors associated with high stage operation will be reduced by the magnitude of the errorless lower stage sampling. Commonly, the lowest stage of ventilation is the minimum stage, where ventilation is required not for temperature regulation, but rather for general air quality maintenance. During this minimum period only a limited number of fans are active and they are cycled on and off at a specific period and duty cycle.

**Baseline Stage Performance Data**

A dataset of high frequency ventilation monitoring from a poultry layer facility, which sampled the activity of ventilation fans instrumented with vibration sensors at one hertz, was used to further define the role of stage control in ventilation error analysis. The ventilation in the test facility was computer controlled based on a four stage ventilation system. Stages 1 and 2 each activated 2 end wall fans, while stages 3 and 4 each activated and additional 4 end wall fans. A four month period from mid February to mid June was analyzed, with results being summarized on a daily basis. Statistics for each day included fan on and off time,
number of on-off fan events, average and median on and off times, and minimum and maximum on and off time durations. These results were summarized for all four fan stages used in the tunnel ventilation scheme of the representative test site.

Analysis of the data yielded many results concerning the response of stage control ventilation systems over time and its impact on ventilation sampling error. First, it was noted that during periods of colder weather, the total ontime of the fans was heavily driven by the stage 1 and 2 fans (Figure 22).

Figure 22. Total fan on-time by ventilation stage for a representative poultry layer facility with tunnel ventilation fans in Ohio.
Secondly, throughout the majority of the sampling period, the percentage of ventilation associated with each fan stage was also heavily dominated by the stage 1 fans during the colder months (Figure 23). During the warmer months though, when the stage 3 and 4 fans were more active, they were a higher component of ventilation mainly based on the fact that these stages had more fans acting during their period than the lower stage controls. The plot of ventilation percentage can also be analyzed as a probability plot for sampling error. The stages that contribute the highest percentage of ventilation also contribute the highest percentage of error when sampled incorrectly.
Furthermore, sampling errors associated with ventilation systems only occurred during changes from active to inactive ventilation events. Stages which demonstrate higher rates of on-off events will provide more opportunities for sampling errors. For the analyzed dataset, the stage 1 or minimum stage ventilation case provided a significantly higher level of on-off events during the daily activities during the colder months. Even during colder months of the study, stage 1 fans continued to oscillate at nearly the same frequency as the higher stage fans. This coincides with the hypothesis that minimum stage systems will have the potential
for greater error sources, independent of the ambient climate, because stage 1 fans do oscillate at a similarly rate to higher stage fans and that the impact of stage 1 fan measurement error is significantly greater than higher stage fans.

Although it was intuitive to assume that the higher stage fans would be cycled on and off for the highest frequency of events during a day period because they are at the peak end of ventilation control, the analysis found this to be untrue (Figure 24). In fact, the stage 1 fans continue to dominate the number of on events due to low nighttime temperatures which drove the system back to minimum ventilation during the period of February through June which was studied. This constant cycling throughout the course of the cooler nighttime period eclipses the cycling of higher stage fans during the midday time frame.
Figure 24. On events per day by ventilation stage for a representative poultry layer facility with tunnel ventilation fans in Ohio.

Finally, the duration of the minimum stage on and off times varied over the duration of the study (Figure 25). This rate was controlled by the automatic ventilation control system and can change depending on the seasonal settings and the ambient weather conditions. Standard ontime intervals of 60, 90, 120, 150, and 180 sec/event were all used by the automatic control system. During the colder periods an ontime of 60 sec/event was used. Beginning on the 9th of March, the weather began to warm and the stage 1 ontime increased to 180 sec/event. A cold weather period on April 8th returned the barn to a lower ventilation cycle,
specifically a 90 sec/event ontime. This was further reduced on April 18th to 60 seconds which coincided with all birds being removed from the test site. The lack of birds removed the only source of heating within the barn and reduced the indoor temperature. After 3 weeks of no bird presence and an additional startup period for the new birds, the ontime eventually increased above 60 seconds and continued to increase with an increase in inlet temperature.

Figure 25. Daily median on-time and inlet temperature for a stage 1 fan in a representative poultry layer facility with tunnel ventilation fans in Ohio.
The period and duty cycle of the minimum stage fans was controlled by the automated ventilation controller. Because the duty cycle is often not 50%, the active signal frequency cannot be represented by the inverse of the period (Figure 26). The true period for the active signal is twice the positive on-time of the signal. When considering the accuracy of measurement for a discontinuous stepwise signal, it was key to note that errors were associated with changes in the signal step, not with accurately determining the step magnitude. The overall measurement error will then be driven by the signal which exhibits the greatest number of changes in magnitude, not the signal with the greatest overall magnitude.

Figure 26. An example timing diagram of minimum stage control period used in a ventilation control system of a tunnel ventilated poultry or swine building.

The Nyquist sampling frequency for continuous time signals states that the sampling frequency should be a minimum of twice the fundamental frequency of a signal. This theorem was based solely on the ability to accurately measure the frequency of continuous signals and cannot be applied to measuring the positive
pulse width of a discrete discontinuous signal. There are three basic sampling conditions that will occur for ventilation monitoring. The sampling interval \((t_s)\) can be equal to, greater than, or less than the minimum on time of the fan \((t_{on})\). When \(t_s\) was equal to \(t_{on}\), then the minimum Nyquist frequency was met. Each case was analyzed individually to determine the measurement error based on sampling rate.

**Case 1:** \(t_s = t_{on}\)

![Figure 27. Sampling diagram for \(t_s = t_{on}\) assuming that no phase lag exists between the leading edge of the input signal and the sampling point.](image)

Case 1 shows that the recorded signal was a perfect replication of the input signal (Figure 27). Problems exist though when the true application of these results are analyzed. First, there is no synchronization of the input signal and sampling interval in a real instrumentation system. This will induce a random phase lag \((\gamma_{sec})\) between the start of the input signal and the start of the sampling interval (Figure 28).
Figure 28. Sampling diagram for $t_s = t_{on}$ with non-zero phase phase lag between the leading edge of the input signal and the sampling point.

The second point of concern was the random differences or delays in the timing of the automated ventilation control and the instrumentation system. It can be widely assumed that the instrumentation system will maintain a high level of repeatability on its sampling interval, but the same cannot be said for the automated ventilation system. Small variations in the system clocks of each device can easily change the frequency of one of the systems and cause the Nyquist criteria to no longer be met. Furthermore, if the input sensor is a positive acting type, such as a vibration sensor which measures true fan activity rather than the latching of a control relay, then $t_{on}$ becomes a random function itself caused by delays in fan startup. These delays can be caused by fan distance from the automated ventilation controller, fan belt tension, fan motor maintenance, differential building pressure, and external weather conditions. Previous results have documented the effect of
these startup and shutdown conditions to cause a 3 – 8 second delay in startup and a 1 – 2 second delay in shutdown for each fan. Applying these results yielded the knowledge that $t_{on}$ will be less than $t_s$, causing the potential for significant errors based on the random time delay and phase delay (Equation 18 and Figure 29).

When $\gamma_{sec} < t_{on}$

$$error = \frac{t_s - t_{on}}{t_{on}}$$

When $t_s > \gamma_{sec} > t_{on}$

$$error = \frac{t_{on}}{t_{on}} = 100\%$$

Equation 18. Emission error based on sampling error and input signal phase lag for synchronous ontime and sampling periods (Derived by Author).

Where: $t_s$ = Sampling time of measurement system

$t_{on}$ = Actual fan ontime of measurement system

$\gamma_{sec}$ = Phase lag of input and sampling interval
Figure 29. Comparison of sampling errors versus fan startup and shutdown times for fan on-time and sampling time equal to 90 seconds.

The probability that $\gamma_{sec}$ is greater than $t_{on}$ can also be directly calculated based on the assumption that $\gamma_{sec}$ is truly a random variable. This assumption is valid because the fan start time and $\gamma_{sec}$ are governed by the internal barn conditions, which are governed by the ambient weather conditions. The result is that $\gamma_{sec}$ can be considered random because it is derived from the randomness of ambient weather conditions (Equation 19 and Figure 30).

$$Probability \quad \gamma_{sec} > t_{on} = \frac{t_{start} - t_{stop}}{t_x}$$

Equation 19. Probability of 100% sampling error based on synchronous on-time and sampling periods (Derived by Author).

Where: $t_{start} = \text{Fan startup delay}$

$t_{stop} = \text{Fan shutdown delay}$
Case 2: \( t_s > t_{on} \)

When the sampling interval was greater than the on-time interval of the fan, the error rates will be highly random based on the phase lag and the actual sampling frequency used. These errors can be expressed fundamentally as (Equation 20):

\[
\text{when } \gamma_{sec} < t_{on} \\
\text{error} = \frac{t_s - t_{on}}{t_{on}}
\]

\[
\text{when } t_s > \gamma_{sec} > t_{on} \\
\text{error} = \frac{t_{on}}{t_{on}} = 100\%
\]

Equation 20. Emission error based on sampling error and input signal phase lag for cases of sampling periods greater than ontime periods (Derived by Author).
These fundamental error equations were the same as was shown in Case 1. The main difference between these representations was that \( t_s \) no longer had any relationship to \( t_{on} \). As the difference between \( t_s \) and \( t_{on} \) grows, the error associated with sampling will also grow.

Case 3: \( t_s < t_{on} \)

The last sampling method deals with sampling multiple times during a single on-time event (Figure 31). Although a cursory look would predict that this method would lead to a reduction in overall measurement error, further evaluation predicts exactly the opposite. In fact, this sampling method can be wrought with errors if not configured properly. Digital data acquisition systems use a sample and hold methodology in which it is assumed that the sampled value is maintained throughout the duration of the sampling period. This can cause error propagation by overestimating the on-time of an input signal.
Figure 31. Sampling diagram for $t_s < t_{on}$ with zero phase lag between the input signal and the sampling point.

When sampling at a frequency which is not triggered by the input frequency, the $\gamma_{sec}$ can change randomly not only over time, but also between input cycles. This causes a high likelihood for error even though the Nyquist criteria is fully satisfied.

The error associated with this sampling type can be described as (Equation 21):

$$ error = \left\{ \begin{array}{ll}
\frac{t_{on}}{t_s} \times t_s - t_{on} & \text{when } t_{on} \mod t_s \\
t_s & \text{when } \gamma_{sec} < (t_{on} \mod t_s)
\end{array} \right. $$

$$ error = \left\{ \begin{array}{ll}
\frac{t_{on}}{t_s} \times t_s - t_{on} & \text{when } \gamma_{sec} < (t_{on} \mod t_s)
\end{array} \right. $$

Equation 21. Emission error based on sampling error and input signal phase lag for sampling periods less than ontime periods (Derived by Author).
Overall error for this case was a combination of both sampling time and ontime. A surface plot was used to create a graphical perspective of the impact each parameter had on the overall measurement error. The surface plot of error for a signal with a 5 minute period and a 30% duty cycle yields a highly variable map of possible measurement error (Figure 32). During the underestimation event as defined by \( \gamma_n > \left( t_{on} \mod t_s \right) \), the error value was directly related to the modulus of the fan on-time and the sampling interval. As the modulus increases, so does the sampling error. The numerator of the error calculation was in fact mathematically identical to the modulus function and results in a prefect correlation factor.
Regression Analysis: Sampling Error versus Modulus of On-time and Sampling Time

The regression equation is: Error = 0.000017 - 0.0111 Modulus

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S = 0.000272509  R-Sq = 100.0%  R-Sq(adj) = 100.0%

Figure 32. Regression analysis of error versus the modulus of sampling time and fan ontime for cases of underestimation of ventilation time.
During periods of overestimation of error, the error value was related to not only the modulus of the fan on-time and sampling interval, but also the magnitude of the sampling interval (Figure 33). Regression analysis again showed that the error equation was mathematically identical to this relationship.

Regression Analysis: Overestimated Error versus Modulus of On-time and Sampling Time

The regression equation is:

\[
\text{Error} = 0.000051 + 0.0111 \text{ Modulus} + 0.0111 \text{ Sampling Time}
\]

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S = 0.000272509  R-Sq = 100.0%  R-Sq(adj) = 100.0%

Figure 33. Regression analysis of error versus the modulus of sampling time and fan on-time and versus the sampling time for conditions of overestimation of error.

The implications of this error analysis were that no singular sampling interval will provide the optimal sampling rate for a specific automatic ventilation control system. The minimum on-time for the minimum stage must be known in
order to accurately predict sampling error. This error will still vary based on the randomness of the start and stop delays associated with the fan dynamics. The error values will also change based on the random time delay function caused by unsynchronized input and sampling systems.

The threshold criteria for errors to be under or over estimated was based solely on the modulus of the fan on‐time and sampling interval. The modulus will repeat as zero for any values which are a common denominator of the on-time. During this event, it is guaranteed that the sample will be underestimated because the random lag time will always be greater than the nulled modulus. An extension of this result is that the overall probability of error will tend towards underestimation. Evaluation of fan on‐times from 240 to 60 seconds in 10 second intervals yields an average probability of 62% that the error will be underestimated over the entire range of sampling intervals.

**Sensitivity of Error to Measurement Technique**

The technique used to measure ventilation activity acts as a much weaker source of error when compared to the sampling frequency. As discussed previously, many methods are available to monitor the activity of fan ventilation systems. Results from previous work as well as further analysis of the high frequency ventilation dataset described previously show that on average an active ventilation sensor will measure 1.74 second less ventilation time than a passive sensors. For the shortest possible fan cycles of 60 seconds, this results in a total error percentage of 2.9%. A select period of 27 days in late March through early April were analyzed
to quantitatively measure the true effect of such sampling errors. During this period both 120 and 180 second minimum stage ventilation times were recorded. The average percent error over the course of this 27 day study was 0.61% (Table 5). Passive sensors would have yielded an overestimate of ventilation of nearly 3 hours total or 6.7 minutes per day.
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<td>352</td>
<td>0.79%</td>
</tr>
<tr>
<td>4/16/2007</td>
<td>2.51</td>
<td>636</td>
<td>1.14%</td>
</tr>
<tr>
<td>Average</td>
<td>1.74</td>
<td>372</td>
<td>0.61%</td>
</tr>
</tbody>
</table>

Table 5. Sampling errors associated with passive ventilation sensors in a tunnel ventilated poultry layer facility over a 27 day period during March and April of 2007.

As derived previously, the fan startup and shutdown times will play a major role in the selection of the optimal sampling interval. This will only be the case though when active ventilation sensors are used. Passive sensors such as relay
monitors or current sensors will provide outputs which are virtually identical to the computer based control signal and thus will have very repeatable and predictable intervals. Further, as just described, the errors associated with these sensors are small in magnitude and will reduce as additional fan stages are activated. The implication of these results is that while active sensors provide an enhanced ability to reduce false positive ventilation signals, they also require additional calculation into their optimal sampling rate to reduce sampling interval errors.

**Evaluation of Measurement Error from Experimental Data**

The three case model used to predict ventilation measurement errors was verified by comparing the model output results to data collected from a CAFO facility at 1 second intervals. The fan studied was operating as the minimum ventilation fan with an on-time of 90 seconds and a duty cycle of 5 minutes. The fan was instrumented with a vibration sensor to detect operation, thus it was expected that the actual on-time of the fan would be less than 90 seconds. Based on these parameters, it was hypothesized that the error will be maximized under conditions where the modulus of the on-time and sampling time maximize. This will occur at points which are near multiples of the on-time, thus the expected error should show harmonics at fundamental frequencies of the on-time.

It was also expected that the overall error will decrease as the length of the sampling period increases. Because signals are both over estimated and under estimated, the central limit theorem will cause the total signal content to average over time and result in a reduced total ventilation error. All analyses calculated the
error response of sampling from 15 to 600 second with 15 second intervals. The first study evaluated the effect of monitoring ventilation during a 3 hour window. The raw 15 second data was used as the true signal data and error calculations were made by comparing the total ventilation time under the test treatments to the ventilation time at the 15 second interval. As predicted, peak errors did occur at the fundamental sampling intervals of 45, 90, 135, and 180 sampling times (Figure 34). Especially alarming was that the 45 second sampling interval had greater error magnitudes than many of the lower frequency sampling periods.

![Figure 34. Measurement error induced by sampling criteria for Stage 1 fans over a three hour duration in a high rise poultry layer facility.](image)
Further tests were conducted to evaluate the decrease in sampling error as the duration of the study was increased. A 12 hour sampling window was evaluated under the same treatment parameters as the 3 hour study (Figure 35). As expected, the overall magnitudes of sampling error were reduced because of the increased sampling interval length. The harmonics of the on-time were again found to be major error sources of error as the 45, 90, 135, and 180 second sampling intervals again exhibited much higher sources of error than other sampling locations.

Figure 35. Measurement error induced by sampling criteria for Stage 1 fan over a 12 hour interval in a high rise poultry layer facility.
A final analysis was conducted to evaluate the sampling error when considering a 24 hour ventilation window. Again, the overall error rates were reduced by longer sampling windows, but the fundamental error frequencies still showed significant error rates (Figure 36).

![Figure 36](image-url)

Figure 36. Measurement error induced by the sampling criteria for a Stage 1 fan over a 24 hour duration in a high rise poultry layer facility.

The results of this analysis showed the importance of understanding the minimum on-time of the fan system in order to reduce the magnitude of error associated with sampling rates. As the duration of the sampling period becomes greater, the magnitude of error will decrease based on the properties of the central
limit theorem. Certain sampling frequencies, specifically those which are intervals of the on-time frequency will be impacted less by the central limit theorem and will require much longer sampling windows to yield an error within an acceptable range. When sufficient information was known about the on-time parameters of the minimum stage control a proper sampling methodology could be designed to minimize measurement error. This methodology would include considerations for both sampling interval and the phase lag of the input signal. Because of the randomness in the phase lag of the input signal measurement errors can never be completely eliminated but they will be minimized by reducing the sampling interval with respect to the on-time.

An alternative to this time based sampling methodology that would completely eliminate measurement errors dealing with sampling intervals would be to develop a trigger based time stamping protocol that would record instantaneous changes in the status of fan signals. External trigger interrupts are commonly used in embedded control applications, but nearly impossible to implement in a personal computer data acquisition application. This is caused by the limitations of digital input capabilities and the high number of fans typically used in large CAFO facilities. A specialized embedded controller could be developed in which multiple external interrupts were provided as general purpose digital input pins. The firmware would monitor the status of the interrupt registers and would precisely time stamp the moment of fan activation to the nearest one instruction cycle. Fan status and proportional on-times could then be transmitted on predefined intervals. The magnitude of error in this alternative approach would be one instruction cycle of the
specific microcontroller. For typical low power microcontrollers, this error time would be less than 1 μsec. This would improve the measurement error rates by several orders of magnitude when compared to current methods, but would also require the development of data acquisition equipment not currently available commercially and a high level of embedded design expertise to ensure a reliable system.

3.5. CONCLUSIONS

A new sensor, composed of entirely electrical components, was developed to monitor the operation of agricultural fans, based on previous work which demonstrated the feasibility to determine fan operational status by vibration measurement. Laboratory testing has shown that the sensor draws less than 1 mA during operation and has a negligible sensitivity reduction when exposed to high moisture conditions or extreme temperature conditions. The new sensor can be easily installed on any agricultural fan which has a hood or other mounting device which will transmit vibration while the fan is running and that the sensitivity of the fan can be adjustable upon installation. Field testing in both swine and poultry applications demonstrated that the vibration sensor provided a stable response to vibration activity and accurately indicated the status of agricultural fans.

It was further found that errors associated with sampling of fan activity sensors can be significant if consideration is not given to the minimum stage ontime conditions of the automated ventilation controller. For Ohio climates, it was found that the minimum stage was most critical for sampling time selection based on the high frequency of on-off control events, each of which provide a source for error.
propagation. Error magnitudes increased as the modulus of the fan on time and sampling time was maximized. It was found that underestimation of ventilation rate was more commonly associated with sampling errors, because of the cyclic nature of modulus calculations. Furthermore, as the measurement interval for ventilation increases, the impact of sampling error will decrease. Over longer time intervals, the Central Limit Theorem causes a balancing of over and under estimations and minimizes the impact of sampling rate. It was also found that the type of ventilation activity sensor will also impact the accuracy of measurement. Passive sensors were found to overestimate ventilation on average 0.61% due to inaccuracies associated with the fan startup times.

Although these results do document a significant improvement in ventilation activity sensing they also bring about new requirement for ventilation data acquisition systems. Traditional stage monitoring sensors would require a single data acquisition channel for several fans operating under the same stage control. With fan specific vibration sensors a single data acquisition channel is needed per individual exhaust fan. In some cases this can cause a 10 fold increase in data acquisition capacity. The potential then exists to pursue advanced sensor networking as a means to interconnect all fan activity sensors through a data bus backbone and allow for ubiquitous data transfer throughout all measurement points. If deployed successfully, only a single point of communication would be required to allow access to fan sensors in real-time. This would reduce both cost and complexity of data acquisition systems required for CAFO monitoring.
CHAPTER 4

EVALUATION OF CONTROLLER AREA NETWORKS FOR CAFO MONITORING

4.1. INTRODUCTION

Controller Area Network systems are ideally suited for linking multiple embedded sensors over a master-master communication network. CAN bus system protocols provide an automatic means of arbitration to schedule urgent messages with higher priorities and can also be easily expanded for future network growth. Although developed for use within automobiles, CAN has been applied to alternative sensor networks.

When considering CAN for use in CAFO environments, a major research concern is its ability to transmit serial data over the long bus lengths required to fully cover a large production facility. General serial transmission theory provides indication that by modifying the baud rate and termination resistances, the network could be optimized for extended range communication, though no such previous work with CAN bus systems has been published.
If successful, long range CAN within CAFO environments would allow the opportunity to install a single, 4-conductor, communication cable throughout the length of the facility and attach a sensor to the communication bus at any point along the way. As a master-master based protocol, these sensor nodes could immediately register on the network and begin to feedback sensor data to the data logger or sink node. Sensors could be relocated or added at any time, granted that the new measurement location was within reach of the communication bus. Data acquisition techniques would also be simplified as a computer based data logger could be connected at any single point along the CAN bus network and allow for real-time access to any measurement point within the CAFO.

4.2. OBJECTIVES

The objective of this work was to evaluate the effectiveness of CAN bus communication in a simulated animal housing environment. Specific objectives include:

a) Development of a CAN bus sensor network for applications in monitoring animal indoor environment and air quality,

b) Identification and testing of critical CAN performance parameters as a function of bus length and data rate, and

c) Determination of a range of operating criteria for successful CAN implementation in livestock facilities.
4.3. METHODS

4.3.1. DESCRIPTION OF EVALUATION HARDWARE

A CAN bus sensor network was developed and tested to evaluate its effectiveness in transmitting sensor data within large animal confinement facilities (Figure 37). This CAN bus network contained several key components including multiple CAN enabled data acquisition nodes, appropriate cabling to link each CAN node, and termination blocks at each end of the CAN bus. Once each sensor node was placed in the desired location, the data transmission lines allowed for multipoint communication between each sensor node and the data logging node.

![Figure 37. Network topology for a CAN bus sensor installation within a confined animal feeding operation.](image)

Although few robust CAN data acquisition systems are commercially available, several standard microcontroller products contain hardware CAN controllers. An 8-bit microcontroller was chosen as the host processor for this project and included
peripherals for CAN implementation, low power consumption, and sufficient analog to digital conversion capabilities. The microcontroller was matched with a CAN transceiver chip to provide the necessary level shifting for CAN bus communication.

A custom designed circuit board was developed to host the microcontroller, transceiver, and all necessary components for their operation. A 20 MHz crystal oscillator was used to provide adequate bit timing for CAN data transfer rates of up to 250 kbits/sec. On-board voltage regulation ensured a stable and noise free power supply for each individual node. Peripheral interfaces were also incorporated to facilitate LCD screen connection for data verification and for external signal conditioning such as analog filtering and amplification.

A daisy-chain wiring approach was adopted for this sensor network and using CAT5 networking cable. The wire had an impedance of 100 ±15 ohm and was commonly used in data transmission applications. RJ45 connectors were used to interface the physical data wires to the node circuit board. Bus termination was accomplished using passive resistor terminators at each end of the network.

Sensor data from each node was stored via a specialized CAN bus data logger. This device integrated a host processor and a Compact Flash storage card. The specialized host processor accepted all CAN bus messages and stored the transmitting identifier and all eight CAN data bytes to the Flash card for post processing.
4.3.2. Identification of Critical Performance Parameters

Serial data transmission, as implemented in CAN bus communication, can be adversely affected by several parameters including signal travel length, data transmission rate (baud rate), impedance of the transmission wire, and the termination quality of the network. Experimental testing was completed to evaluate the effect of bus length and data transmission rate on the integrity of CAN message transmission. Three commonly used data transmission rates were evaluated: 50, 100, and 250 kbits/sec. These were selected due to their wide use in CAN implementation protocols. Each baud rate was evaluated over varying bus lengths from 100 to 600 meters. Two communication nodes and one data logging node were used for each test and a successful message transmission was determined by noting whether messages were successfully passed without error from one end of the network bus to the other. Although this digital qualification ultimately determined if the bus parameters permitted data transmission, several analog data transmission measurements were recorded to quantify the amount of attenuation and distortion present in each message.

Data transmission errors are based on two unique sources. First, the signal attenuation increased as the bus length increased. This can be estimated quite accurately based on the wire datasheets provided by the wire manufacturer. A second type of signal distortion existed due to data transmission reflections. By properly sizing the termination resistors at the manufacturers suggested value of 118 ohms, this reflection was minimized during this study.
During ideal conditions, the nominal CAN differential signal exhibited an amplitude of 2 volts. The transceiver would correctly recognize any differential dominant (digital logic 0) signal as greater than 1 volt and any differential recessive (digital logic 1) signal as less than 0.5 volts (Figure 38). If the reflected wave had a significant amplitude, it was possible that the superimposed reflected wave would have a magnitude greater than 0.5 volts and thus could cause bit errors during message transmission. Likewise, if signal attenuation reduced the dominant signal to less than 1 volt bit errors could occur.

![Logic pattern for recognition of recessive and dominant bits by a CAN bus transceiver.](image)

**Figure 38.** Logic pattern for recognition of recessive and dominant bits by a CAN bus transceiver.

### 4.3.3. **Testing Method and Plan**

In order to evaluate the CAN bus for each of the parameters discussed above, a series of laboratory tests were conducted over varying bus lengths (100, 140, 180, 300, 450, and 600 m) and data transmission rates (50, 100, and 250 kbits/sec). The results of the laboratory test were then verified by installing a CAN bus data acquisition system at a poultry production facility.

For the laboratory testing, two transmission nodes were connected via a specified length of CAT5 wire and an oscilloscope was used to analyze the data.
signal at different points along the bus (Figure 39). A third node was added to log CAN message data which was used to validate successful message transmission. CAN Node 1 was configured as the transmission node and CAN Node 2 was configured as the receiving node.

![Figure 39. Schematic of benchtop CAN bus testing layout evaluated under bus lengths of 100 to 600 meters and data transmission rates of 50 to 250 kbits/sec.](image)

![Figure 40. Graphical description of critical data transmission parameters for individual CAN bus message bits.](image)
At the receiving node, the following parameters were measured (Figure 40):

- Differential signal voltage, $V_d$
- Differential signal rise time, $T_r$
- Maximum to critical transition voltage, $V_a$
- Maximum to critical transition time, $T_a$
- Critical voltage, $V_c = 0.5$ volts based on MCP2551 specifications
- Critical decay time, $T_c$

At the transmitting node, the following parameters were measured (Figure 40):

- Reflection imposed delay time, $T_b$
- Reflection imposed voltage, $V_b$

The differential signal voltage $V_d$ indicates the overall strength of the transmission signal. This voltage was maximized at 2 volts for all tests discussed in this paper and was controlled by the CAN transceiver. A reduction from the maximum voltage indicates attenuation loss due to cabling impedance. The time required to reach the steady state $V_d$ level for each test was defined as the differential signal rise time ($T_r$). The CAN transceiver was configured for an infinite slew rate, thus the rise time should have been very close to zero during testing.

The maximum to critical transition voltage was measured as the voltage drop between the measured maximum differential bus voltage level and the transceiver critical voltage level of 0.5 volts. Mathematically, this could be calculated as the maximum differential voltage level minus 0.5 volts. The time required to reach the critical voltage level was also recorded as the maximum to critical transition time ($T_a$). Theoretical transceiver performance indicates that the transition time should
be very close to zero under normal operating situations. The critical time (Tc) was also measured to determine the decay time from after a reflection situation to a fully decayed signal.

The final two measurement points quantified the reflected signal. The reflected voltage measured the maximum voltage level produced by the reflected data and the reflection time measured the time required for the reflection to decay from the system. As the reflection time increased for high data transmission rates, it becomes likely that the reflected signal can carry over to the next bit time and cause bit errors.

The CAN datalogging node was also used to quantify successful message transmission. The transmission nodes were programmed to send data at a frequency of 10 hertz. The CAN datalogger time stamped each transmitted message and postprocessing was done to validate that messages were successfully transmitted at the 10 hertz frequency.

4.4. RESULTS AND DISCUSSION

4.4.1. Effect of Bus Length and Baud Rate

A series of tests were conducted at 50, 100, and 250 kbits/sec and over a bus length of 100, 140, 180, 300, 450, and 600 meters. General performance data for the CAN system under various operating methods are shown below in Table 6, Table 7, and Table 8.
Table 6. Data transmission performance for CAN bus system operating at 50 kbits/sec baud rate and various bus lengths.

<table>
<thead>
<tr>
<th>Bus Length (m)</th>
<th>Vd (Volts)</th>
<th>Tr (μsec)</th>
<th>Ta (μsec)</th>
<th>Va (Volts)</th>
<th>Tb (μsec)</th>
<th>Vb (Volts)</th>
<th>Tc (μsec)</th>
<th>Vc (Volts)</th>
<th>Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.780</td>
<td>0.200</td>
<td>0.060</td>
<td>1.280</td>
<td>0.000</td>
<td>0.000</td>
<td>0.612</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>140</td>
<td>1.700</td>
<td>0.300</td>
<td>0.072</td>
<td>1.200</td>
<td>0.000</td>
<td>0.000</td>
<td>0.628</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>180</td>
<td>1.600</td>
<td>0.400</td>
<td>0.096</td>
<td>1.100</td>
<td>1.800</td>
<td>0.300</td>
<td>0.850</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>300</td>
<td>1.420</td>
<td>0.640</td>
<td>0.196</td>
<td>0.920</td>
<td>2.860</td>
<td>0.420</td>
<td>1.080</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>450</td>
<td>1.260</td>
<td>1.040</td>
<td>0.260</td>
<td>0.760</td>
<td>4.220</td>
<td>0.500</td>
<td>1.980</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>600</td>
<td>1.120</td>
<td>1.120</td>
<td>0.300</td>
<td>0.620</td>
<td>5.800</td>
<td>0.560</td>
<td>2.080</td>
<td>0.500</td>
<td>Y</td>
</tr>
</tbody>
</table>

Table 7. Data transmission performance for CAN bus system operating at 100 kbits/sec baud rate and various bus lengths.

<table>
<thead>
<tr>
<th>Bus Length (m)</th>
<th>Vd (Volts)</th>
<th>Tr (μsec)</th>
<th>Ta (μsec)</th>
<th>Va (Volts)</th>
<th>Tb (μsec)</th>
<th>Vb (Volts)</th>
<th>Tc (μsec)</th>
<th>Vc (Volts)</th>
<th>Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.780</td>
<td>0.150</td>
<td>0.060</td>
<td>1.280</td>
<td>0.740</td>
<td>0.280</td>
<td>0.460</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>140</td>
<td>1.700</td>
<td>0.252</td>
<td>0.076</td>
<td>1.200</td>
<td>1.050</td>
<td>0.300</td>
<td>0.496</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>180</td>
<td>1.600</td>
<td>0.292</td>
<td>0.100</td>
<td>1.100</td>
<td>1.860</td>
<td>0.340</td>
<td>0.568</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>300</td>
<td>1.420</td>
<td>0.432</td>
<td>0.190</td>
<td>0.920</td>
<td>2.860</td>
<td>0.440</td>
<td>0.850</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>450</td>
<td>1.280</td>
<td>0.528</td>
<td>0.250</td>
<td>0.780</td>
<td>4.240</td>
<td>0.500</td>
<td>1.200</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>600</td>
<td>1.020</td>
<td>0.752</td>
<td>0.230</td>
<td>0.520</td>
<td>5.240</td>
<td>0.520</td>
<td>1.410</td>
<td>0.500</td>
<td>Y</td>
</tr>
</tbody>
</table>
Table 8. Data transmission performance for CAN bus system operating at 250 kbits/sec baud rate and various bus lengths.

<table>
<thead>
<tr>
<th>Bus Length (m)</th>
<th>Vd (Volts)</th>
<th>Tr (μsec)</th>
<th>Ta (μsec)</th>
<th>Va (Volts)</th>
<th>Tb (μsec)</th>
<th>Vb (Volts)</th>
<th>Tc (μsec)</th>
<th>Vc (Volts)</th>
<th>Success</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1.760</td>
<td>0.116</td>
<td>0.072</td>
<td>1.260</td>
<td>0.980</td>
<td>0.220</td>
<td>0.276</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>140</td>
<td>1.680</td>
<td>0.220</td>
<td>0.086</td>
<td>1.180</td>
<td>1.420</td>
<td>0.260</td>
<td>0.340</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>180</td>
<td>1.600</td>
<td>0.280</td>
<td>0.104</td>
<td>1.100</td>
<td>1.800</td>
<td>0.320</td>
<td>0.472</td>
<td>0.500</td>
<td>Y</td>
</tr>
<tr>
<td>300</td>
<td>1.460</td>
<td>0.460</td>
<td>0.172</td>
<td>0.960</td>
<td>2.980</td>
<td>0.460</td>
<td>0.680</td>
<td>0.500</td>
<td>C1</td>
</tr>
<tr>
<td>450</td>
<td>1.340</td>
<td>0.670</td>
<td>0.310</td>
<td>0.840</td>
<td>3.900</td>
<td>0.360</td>
<td>1.050</td>
<td>0.500</td>
<td>C2</td>
</tr>
<tr>
<td>600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N</td>
</tr>
</tbody>
</table>

Theoretically, bus communication errors will occur when the reflection voltage (Vb) was greater than 0.5 volts and the reflection time was greater than one half of the bit time, or when the differential signal voltage was less than 1 volt. In practice, actual bus communication is affected by other factors inherent to the CAN transceiver and host processor, so true communication must be verified through testing. During testing, all bus lengths for 50 and 100 kbits/sec allowed successful message transmission. This was based on all messages being successfully transferred between the two test nodes and successfully recorded by the data logging node. For the 250 kbits/sec test, successful message transmission was only attainable up to the 180 m bus length. At the 300 m bus length occasional messages were repeated unnecessarily due to mistaken acknowledgement bit recognition (C1). The reflection voltage, Vb, for this bus length was 0.460 volts, which was very close to the critical value of 0.5 volts for bit errors to occur. Acknowledgement bit error messages accounted for less than 10% of all transmitted messages at the 300 m bus length. Bit errors also existed at 450 meters, although on a much larger scale (C2). Unexpectedly, for the 250 kbits/sec tests, the reflection voltage, Vb, was lower
under the 450 m bus length than the 300 m bus length. The cause of this anomaly was not unknown, although this response was repeated under further testing. Above 450 meters, message transmission was unattainable.

As expected under all baud rate conditions, the differential voltage signal attenuation increased as the baud rate increased. This is shown as the general trend for $V_d$ declines as the bus length increases. Testing determined that none of the evaluated baud rates and bus lengths produced a signal amplitude below the threshold dominant level of 1 volt for the transceiver.

Signal reflection was measured in significant magnitude and was denoted above by $T_b$ and $V_b$. In most cases though, the magnitude of $V_b$ was less than 0.5 volts and thus did not affect the accuracy of data transmission.

Minor data transmission errors occurred during the 250 kbits/sec testing with 300 and 450 m bus lengths due to a lack in acknowledgment bit recognition by the transmitting node. Near the end of the CAN message there are two acknowledgement bits. The transmitting node transmits both of these bits as recessive. All nodes that receive the message will acknowledge the transmitter by driving the first bit dominant (Darr, 2004). During this study, the receiving node indicated that the message was successfully acquired without errors and should have driven the second recessive acknowledgement bit dominant as an indication to the transmission node that at least one listener was present. The assertion of this bit was unsuccessful and unrecognizable due to signal attenuation and reflectance of the data signal.
4.4.2. Multi-Sensor Field Trial

A field trial of a CAN Bus data acquisition system was conducted at a poultry production facility in Ohio during March and April 2006. The high-rise building was 200 meters long and 21 meters wide and housed approximately 170,000 hens. The CAN Bus network was setup along the outside wall of the building and was used to monitor the status of 3 individual fan stages (Figure 41). The total length of the installed CAN Bus was 100 meters. The baud rate of the CAN Bus for this test was set at 250 kbit/sec. On each of the 3 fans being monitored, a vibration sensor was installed which provided a positive 5 volt signal when the fan was operating and a 0 volt signal when the fan was stationary (Figure 42). A single CAN Bus transmission line was run along the building to allow all three nodes to communicate. The total length of the CAN Bus transmission line was 90 meters, with equal 30 meters sections connecting each of the nodes. This bus length was less than tested during the long range CAN evaluation, but was very typical of the data transmission requirements necessary for confined animal feeding operations.
Figure 41. CAN bus node placement along an external fan wall of a confined animal feeding operation.

Figure 42. CAN bus placement and connection to a vibration sensor used to monitor the activity status of a single speed exhaust fan at a confined animal feeding operation.
The CAN Bus nodes were programmed to acquire data from the vibration sensor and to transmit the current fan status over the CAN Bus at a rate of 1 Hz. The individual CAN messages were complied by a fourth CAN Node and this data was logged to a data acquisition computer. The data presented in this paper was collected over a range of 8 days from March 27th to April 3rd. Communication Errors, were recorded when a CAN Bus message was not received from a specific node during the sampling interval.

During the sampling period there was a significant difference between the error rates of the three communication nodes. Nodes #1 and #2 performed excellent, each posting Communication Error rates of 0.06% and 1.9% respectively. Node #3 performed below expectations and had a total of 6583 Communication Errors which was 10.9% of all messages transmitted from that node. Time series analysis of the errors from Node #3 showed that the errors were grouped into blocks of time when the node was operating correctly and other blocks where errors were occurring (Figure 43). Further analysis also showed that Communication Errors between nodes were uncorrelated and independent between groups.
Attempts were made to identify the cause of communication errors in each of the major error periods for Node #3, but no conclusive determination was found. The authors did find that the manufacturing quality of the Node #3 circuit board was significantly lower than that of Nodes #1 and #2. The embedded firmware of all three nodes was identical.

4.4.3. Sensor Networking Benchmarking

When compared with other industrial data transmission networks such as Ethernet, 802.11 Wireless Ethernet, IEEE 801.15.4, IEEE 802.15.1, RS-232, and RS-485, CAN Bus system exhibit a variety of enhanced qualities. Wired networks are inherently more reliable than wireless systems, because their transmission strength
will not change as a function of the building environment. Wireless data signal are absorbed by organic objects and can adversely affected by changes in the number and size of animals present in an animal production facility. Also, CAN Bus networks allow for point-to-point and point-to-multipoint communication directly from any individual node without requiring the data be passed through a single network master or router. This increases the transmission latency and allows for a truly daisy-chained communication bus to minimize wiring installation. The CAN network topology also allows for additional nodes to be integrated into present systems with minimal effort.

Effective bandwidth is also an advantageous characteristic of CAN Bus systems. CAN messages carry very small overhead, which helps enable efficient sensor and control data transfer. Only 64 bits per message are used for addressing and error checking. This is much less than the addressing requirements of standard 802.11 wireless systems or other wired ethernet messages. At the same time, CAN data transfer rates are higher than those used in other commercial systems such as RS-232, IEEE 802.15.1, and IEEE 802.15.4.

4.4.4. **CAN Bus Bandwidth Capacity Approximation**

Due to the size of current animal production facilities, it is common for several hundred sensor measurements to be recorded simultaneously to fully characterize the building environment. As a traditional rule, most CAN networks should be designed to operate at 35% of the maximum bus capacity. This is done to allow for segments of increased bus traffic and to ensure that critical messages are able to
quickly reach the network. The use of CAN bus systems for general data acquisition can extend the bus load capacities since the frequency and length of each message is already known and since critical control messages are not being transmitted. Based on these parameters a bus load of 70% capacity is suitable for data collection applications in CAFOs.

Transmission Units are defined as the total number of 8 byte data messages that can be transmitted per second over a single network. A single node may send several transmission units depending on the number of sensors interfaced with that particular node. The maximum number of transmission units can be calculated if the data rate and target maximum bus load are known (Equation 22).

\[
Transmission Units \left( \frac{Messages}{Second} \right) = \frac{DataRate \left( \frac{bits}{sec} \right) \times BusLoad(\%)}{134 \left( \frac{bits}{message} \right)}
\]

Equation 22. Calculation of transmission units for CAN bus networks (Derived by Author).

<table>
<thead>
<tr>
<th>Data Rate (kbits/sec)</th>
<th>Number of Transmission Units per Second</th>
<th>Number of 16 bit Sensor Data Points per Second</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>261</td>
<td>1044</td>
</tr>
<tr>
<td>100</td>
<td>522</td>
<td>2088</td>
</tr>
<tr>
<td>250</td>
<td>1305</td>
<td>5220</td>
</tr>
</tbody>
</table>

Table 9. Summary of sensor networking capacity for a CAN bus system operating at a 70% bus load and sensor resolution of 16 bits.
Based on a 70% bus load and a baud rate of 250 kbits/sec, up to 5220 16-bit sensor values can be transmitted over a CAN bus per second (Table 9). If the data rate was reduced to 50 kbits/sec to increase the bus length, then a sensor load of 1044 16-bit values per second is achievable. When applied to air quality monitoring, a network of 1044 sensors with a single data acquisition point would greatly improve researchers current ability to monitoring dynamic changes within large scale confined animal housing operations.

For practical implementation within a CAFO, sensors are required for intensive data acquisition of temperature, relative humidity, and fan activity as well as barn specific sensors such as activity of feeding and manure removal systems, light intensity, animal activity, and production monitoring. Traditional large scale CAFOs may have up to 100 fans per barn and can require any number of indoor sensors depending on the sampling density required. A 200 by 30 meter poultry facility for example with an environmental measurement density of 10 meters$^2$ would require a total of 600 sensors. When collected at a one hertz sampling frequency along with a maximum of 100 fan sensors, the network would need to support a 700 sensor data points per second. This is below the 1044 data point capacity for a 50 kbit/sec sensor network (Table 9). A measurement density of 10 meters$^2$ far exceeds current measurement methodology, but clearly shows the capabilities of a CAN Bus system for highly concentrated and distributed sensor networking for such applications.
4.4.5. Commercial Implementation of CAN Bus

The CAN bus system discussed in this paper was designed specifically for the purpose of air quality data acquisition and is not commercially available. Several other distributed network systems are commercially available, some of which do employ a CAN bus communication protocol. Selection and implementation of such a system requires selecting the required number of nodes, determining the data acquisition capacities of each node, and selecting a methodology to record the sensor information. The data acquisition capacity of each node will consist of selecting the required number of analog and digital input channels. The sensor network software will allow the user to set the sampling interval for the network, and will provide a method of data storage.

4.5. CONCLUSIONS

Based on this work it was found that 50 kbit/sec and 100 kbit/sec baud rate CAN bus data can be successfully transmitted up to 600 meters. This will allow in excess of one-thousand 16-bit sensor data points to be collected per second at a data rate of 50 kbits/sec and over two-thousand 16-bit sensor data points at a data rate of 100 kbits/sec. Although message transmission was successful at long bus lengths of 600 m, attenuation and reflection were present within the digital signal. These parameters must be closely monitored in any long range CAN application to ensure that they are within tolerable limits.

In field testing of a CAN Bus data acquisition was conducted at a poultry production facility to monitor the activity of exhaust fans. The CAN Bus system was
very simple to install and additional nodes can be quickly added by inserting a junction into the network bus. The CAN Bus system displayed high accuracies in transmitting correct sensor information, but did sustain a significant level of communication errors. Given the harsh thermal and chemical environment surrounding the CAN Nodes, the quality and packaging of commercial CAN devices should be evaluated before installation in an animal production facility.

Although CAN bus sensor networks demonstrate improvements to current data acquisition techniques, they still exhibit levels of instability that are not acceptable for research grade data acquisition. It was also noted that in CAFO applications, CAN bus systems do decrease the overall robustness of data collection because of their single bus topology. If a bus failure occurred at any point along the network, all communication would be lost between any sensor and the data acquisition system. These bus failures could be caused by natural events such as wire corrosion or by unexpected faults such as animal or building damage to the CAN cable. To prevent the potential for such failures, the network would require modification to allow for multi-path communication between multiple points. Such a protocol, which could allow redundant data routes and freedom from mechanical cable damage, could further enhance the current standard for CAFO data acquisition systems.
CHAPTER 5

MODELING AND VERIFICATION OF WIRELESS SENSOR PERFORMANCE
IN A POULTRY LAYER FACILITY

5.1. INTRODUCTION

Wireless communication systems provide several characteristics that make them advantageous for use in CAFO monitoring. First, since they are able to transfer data without physical cabling, which is the prime source of failure in wired systems, wireless sensors provide an enhanced reliability feature not seen in traditional wired network systems. Furthermore, wireless sensors provide the ability to truly locate sensors without limitations of the physical environment barriers.

Challenges exist though in applying wireless technology to monitoring CAFO environments. No previous work has documented the electromagnetic environment within a highly concentrated CAFO facility, which limits researchers’ ability to design an appropriately powered network. CAFO facilities also provide extreme challenges in covering the entire building structure with a wireless backbone. Dense population of animals and holding cages are typical for larger production facilities
and will require a network which has the ability to employ multiple router systems to assist in network coverage.

A model to describe the internal electromagnetic environment of a CAFO would be extremely helpful in designing usable data acquisition systems. Specifically, path loss information related to signal attenuation within CAFOs would allow future researchers to employ a totally wireless solution for intensive monitoring of macro and micro climates.

5.1.1. Fundamentals of Wireless Performance Assessment

Path loss through the CAFO environment will attenuate the strength of the wireless sensor data by many physical mechanisms (Figure 44). Signal reflection will occur when the electromagnetic radiation is reflected off the metal structural surfaces. This will occur both on the building walls and also on the cages in which the animals are housed. When signals are reflected two different consequences can occur. First, the signal may be scattered in such a way that it is redirected away from the receiver and the message becomes lost. Secondly, the signal may be received by the receiver after a finite number of reflections. This multiple reflection case causes two separate problems related to reliable data transfer. When the signal is reflected it is forced to travel a longer distance before it reaches the receiver. This increase in path length causes an increase in path loss based on Friis’ formula. Also, since it is possible that a portion of the same signal was received without reflection, the reflected signal will often be a source of multipath interference.
Multipath interference is the phenomena in which two signals of the same magnitude arrive at the receiver out of phase. The phase lag of the delayed signal is typically caused by reflections of the signal within the electromagnetic environment. The addition of out of phase signals will result in an attenuated output that does not properly represent the original signal. This interference level is most widely experiences in amplitude modulated transmission systems.

Signal diffraction occurs when an electromagnetic wave passes through an object containing a sharp or semi-sharp edge. Just like reflected waves, diffracted waves will alter their path of travel. Diffracted waves can be either redirected away from the receiver all together or can add to multipath interference. Within CAFOs, signal diffraction will provide a major component of path interference. Cages are used primarily in the poultry industry to contain the birds within a confined location. These cages will act as sharp edges and will continuously diffract radiated signals.

Signal absorption occurs when the radiated energy is absorbed into the medium it is passing through. Rather than the energy being dissipated in another direction as with signal reflection, absorbed signals are dissipated directly within the medium. Within CAFO facilities, multiple sources of absorbers exist including animals, building materials (concrete and wood), and manure. Previous work has diagnosed the loss parameters of building materials in a commercial setting, but little research has been conducted concerning the loss parameters in agricultural environments.
Shadowing occurs when a receiver is not in the line of sight of the transmitter nor is it in the line of sight of any reflection surfaces. This is typically in outdoor environments, but should be a minor factor in electromagnetic losses in CAFOs given the tightly enclosed nature of these facilities. Shadow environments may occur in annex or adjacent spaces.

Figure 44. Expected path loss mechanisms within a CAFO.

Thus the total path loss through a CAFO environment in decibels can be represented as (Equation 23):

\[ P_r = G_r + G_t + P_t - L_o - L_{ref} - L_{mp} - L_{abs} - L_{abs} - L_{diff} - L_{shad} \]

Equation 23. Expected path loss factors with a CAFO facility (Derived by Author).
Where:

\[ P_r = \text{Power received (dB)} \]
\[ G_r = \text{Receiver antenna gain (dB)} \]
\[ G_t = \text{Transmitting antenna gain (dB)} \]
\[ P_t = \text{Power transmitted (dB)} \]
\[ L_o = \text{Path loss in free space (dB)} \]
\[ L_{\text{ref}} = \text{Path loss due to signal reflection (dB)} \]
\[ L_{\text{mp}} = \text{Path loss due to multipath errors (dB)} \]
\[ L_{\text{absa}} = \text{Path loss due to animal absorption (dB)} \]
\[ L_{\text{absm}} = \text{Path loss due to building material absorption (dB)} \]
\[ L_{\text{diff}} = \text{Path loss due to diffusion (dB)} \]
\[ L_{\text{shad}} = \text{Path loss due to shadowing (dB)} \]

5.2. OBJECTIVES

The objective of this work was to enhance the application of wireless technologies in CAFO facilities through an improved understanding of the path loss of electromagnetic signals inside CAFO environments.

Specific objectives include:

a) Evaluate theoretical path loss models as a means to predict wireless signal attenuation,

b) Establish empirical models on wireless signal path loss with a poultry CAFO,

c) Develop and evaluate a 2D signal attenuation model for predicting path loss, and
d) Verify the 2D signal attenuation model by direct measurement of attenuation in a similar but physically different test facility.

5.3. METHODS

5.3.1. TEST FACILITY SELECTION

Although swine, bovine, and poultry CAFOs are all of major concern regarding air quality measurement, poultry operations exhibit the most challenging environment for wireless sensing due to their high stocking density and wide use of elevated cages to hold animals. Thus poultry layer facilities will be the focus production type for this study. It can be assumed that many of the model verifications completed by this work will transfer easily to other CAFO industries, because the models are based on fundamental principles of wireless data transfer.

Two poultry layer barns in western Ohio served as the primary test facility for this study. These barns were belt battery types which have been retrofitted from a high rise facility. This provided a unique research site in which verification was possible for both typical belt battery barns with multiple cages of animal separation and with verification of high rise specific parameters such as concrete floors separating multiple levels of the facility. These facilities also represented the scale of typical large layer facilities in that they were both 400 feet long and 60 feet wide. When fully stocked, each barn held nearly 250,000 layers. Empirical models were created based on the performance data collected in a single test facility (Barn 3). The second facility (Barn 4) was used to confirm the empirical model results and to evaluate the variability in path loss data between buildings.
5.3.2. Analysis of Theoretical Performance of Wireless Sensors in Confined Animal Feeding Operations

A theoretical model of wireless sensor performance can be very beneficial in understanding the key aspects of signal attenuation and the factors which impact performance. Models that have been verified to be accurate can also be a resource for future analysis of wireless sensors in similarly designed environments. The fundamental starting point for any model dealing with wireless sensor performance is the Friis' equation for free space path loss (Equation 24).

\[ P_r = G_r G_t \left( \frac{\lambda}{4\pi r} \right)^2 P_t \]

Equation 24. Friis free space path loss model (Bansal, 2004).

Where:
- \( P_r \) = Power received (dB)
- \( P_t \) = Power transmitted (dB)
- \( G_r \) = Receiving antenna gain (unitless)
- \( G_t \) = Transmitting antenna gain (unitless)
- \( r \) = Separation distance of the antennas (m)
- \( \lambda \) = Wavelength of the signal (m)

Based on typical wireless sensor nodes operating in the 2.4 GHz band with antenna gains of 0 dBi (\( G_r = G_t = 1 \)) at the transmitter and receiver the path loss can be calculated as a function of linear distance (Equation 25). For this calculation, the
frequency will be assumed to be 2.5 GHz which is at the midpoint of the 2.4 GHz band. This frequency leads to a wavelength of 0.1223 m.

\[ P_r = G_r G_t \left( \frac{\lambda}{4\pi r} \right)^2 P_i \]
\[ \frac{P_r}{P_i} (dB) = 10 \log \left[ G_r G_t \left( \frac{\lambda}{4\pi r} \right)^2 \right] \]
\[ \frac{P_r}{P_i} (dB) = 10 \log \left[ 1 \times 1 \left( \frac{0.1223}{4\pi r} \right)^2 \right] \]
\[ \frac{P_r}{P_i} (dB) = 10 \log \left[ 9.48 \times 10^{-5} \left( \frac{1}{r} \right)^2 \right] \]
\[ \frac{P_r}{P_i} (dB) = 10 \log \left[ 9.48 \times 10^{-5} \right] + 10 \log \left[ \left( \frac{1}{r} \right)^2 \right] \]
\[ \frac{P_r}{P_i} (dB) = -40.23 + 10 \log [r^{-2}] \]

\[ \frac{P_r}{P_i} (dB) = -40.23 - 20 \log [r_{meters}] \]

or

\[ \frac{P_r}{P_i} (dB) = -29.91 - 20 \log [r_{feet}] \]

Equation 25. Derivation of Friis’ free space path loss model based on unit gain conditions and operating within the 2.4 GHz frequency band (Derived by Author).

Waves reflected off the surface of a solid floor will also cause signal attenuation through direct interference with non-reflected waves. Specifically, these reflected waves will arrive at the receiver, out of phase with the non-reflected waves. This phase shift will cause a decrease in overall signal quality. Mathematically, this
phenomena can be characterized by understanding the time delay of the signal and can be represented as (Equation 26):

\[
\frac{P_r}{P_t} (dB) = 10 \log \left[ 4 \sin^2 \left( \frac{2 \pi h_r h_t}{\lambda r} \right) \right]
\]


Where: 
- \( P_r \) = Power received (dB)
- \( P_t \) = Power transmitted (dB)
- \( h_r \) = Height of transmitter (m)
- \( h_t \) = Height of receiver (m)
- \( r \) = Separation distance of the antennas (m)
- \( \lambda \) = Wavelength of the signal (m)

This reflection model though has been found to only be significant when \( r \gg 5 \frac{h_t}{h_r} \) (Linmartz, 2001). For CAFO environments, facilities with very large separation distances and very low lying sensors, reflection path loss can be a significant factor (Figure 45). This is a significant result because many objectives related to CAFO environment research seek to understand the microclimates located directly at the animal level. As such, the sensors often require placement on or near the floor surface. Not only will the animals themselves be significant obstructions, but the floor reflection will also supply a major factor in the overall path loss.
Cages within poultry CAFO facilities are another major factor affecting the performance of wireless sensors. Cages offer a much more difficult prediction challenge in that they are composite bodies made up of steel feeding systems, open cage areas, and many individual animals. When the wireless transmitters are located near the top level of the cages, diffraction can accurately predict path loss when the leading edge of the obstacle is a steel structure. The steel edge of the external feeders is similar in shape to knife edge obstructions. Under these conditions the following path loss models apply (Equation 27):

\[
\frac{P_r}{P_t}(dB) = \begin{cases} 
0 & \nu \leq -1 \\
20 \log \left[ 0.5 - 0.62 \nu \right] & -1 \leq \nu \leq 0 \\
20 \log \left[ 0.5 e^{-0.95\nu} \right] & 0 \leq \nu \leq 1 \\
20 \log \left[ 0.4 - \sqrt{0.1184 - (0.38 - 0.1\nu)^2} \right] & 1 \leq \nu \leq 2.4 \\
20 \log \left[ \frac{0.225}{\nu} \right] & \nu > 2.4 
\end{cases}
\]

Where: 
- \( P_r \) = Power received (dB)
- \( P_t \) = Power transmitted (dB)
- \( \nu \) = Fresnel-Kirchhoff Diffraction Parameter (unitless)

\[
\nu = h \frac{2 (d_1 + d_2)}{\lambda (d_1 \times d_2)}
\]


Where: 
- \( d_1 \) = Distance from transmitter to peak deflector (m)
- \( d_2 \) = Distance from receiver to peak deflector (m)
- \( h \) = Height of peak (m)
- \( \lambda \) = Wavelength of the signal (m)
For a poultry operation with a one aisle separation of 2.26 m and a wireless sensors placed 0.1 m below the top edge of the cages, the path loss can be predicted by (Equation 29):

\[ \nu = 0.1m \sqrt{\frac{2 (1.13 + 1.13)m}{0.1223m(1.13 \times 1.13)m}} = 0.538 \]

\[ \frac{P_L}{P_1} (dB) = 20 \log \left[ 0.5e^{-0.95x0.538} \right] \]

\[ \frac{P_L}{P_1} (dB) = -10.4dB \]

Equation 29. Example calculation of diffraction path loss (Derived by Author).

A theoretical prediction of path loss through poultry cages is complicated by many factors including the wide variations in material cross section of a cage and the variation in density of materials along the length of the cage. At any given point along the length of a cage, wireless signals would be required to pass through a mixture of steel, animals, feed, water lines, and small cavities of free space. The electromagnetic energy would bounce off the many reflective surfaces until a portion of the signal passed clearly through the interior of the cage. This attenuation pattern would repeat for subsequent cages and exhibit a much greater power loss than other path loss methods. A series of experimental studies will be conducted to quantify this path loss caused by transmission through the interior of animal cages.
5.3.3. Specification and Design of a Test Fixture

A test fixture was designed to experimentally quantify the path losses within a CAFO and verify the theoretical path loss models. A Telegesis ETRX1 Zigbee module was chosen to act as the base wireless sensor. This module was chosen based on the following factors:

- Commonality with other commercial wireless sensors
- Small form factor
- Embeddable antenna
- Serial interface for microcontroller operation
- Controllable transmission power
- Low power consumption

The ZIGBEE module provided the following hardware specifications relevant to its path loss and performance in a CAFO environment.

- Adjustable transmission power from 0 dBm to -32 dBm
- Antenna gain of 0 dBi
- Receiver sensitivity of -90 dBm
- 2.4 GHz operating frequency

Two ZIGBEE modules were used to calculate the path loss between two static points within a CAFO. One module acted as the transmitter while the other was a receiver in a point-to-point network connection. An embedded controller (Flash Core B, Tern Inc., Davis, CA) was interfaced to the receiver and was used to control the flow of communication. At a 0.5 hertz interval, the FlashCore B issued a
command that initiated a wireless transmission between the transmitter and receiver. The receiver then reported the RSSI value of the transmission back to the FlashCore B for permanent storage. A keypad was used to allow the operator to enter the transmission distance between the transmitter and receiver, which was logged along with the signal strength information.

Although the ETRX1 modules were Zigbee compatible, they were used only for point-to-point communication during the verification of the path loss models. The ZIGBEE modules are representative of other frequency modulation based wireless transmitters available commercially and the path loss results recorded from the ZIGBEE modules can easily be applied to other modules.

The ZIGBEE modules were mounted to a custom designed circuit board which provided an interface with a microcontroller as well as external power regulation, an RS232 level shifter, and external sensors. The board was fitted with a edge connector (Deutsch Model DTM13-12PA-12PB-R008) and placed in a plastic enclosure (Deutsch Model EEC-325X4B). The plastic enclosure did assert a limited path loss, but for long term CAFO operations it is critical to maintain a completely sealed wireless sensor and prevent corrosion caused by gasses and dust present in CAFO buildings. The ZIGBEE internal chip antenna would also provide less performance than a full whip or other high gain antenna design, but the internal chip antenna was more representative of what would typically be used in a CAFO environment.
5.3.4. **Parameters to Quantify Wireless Performance**

**Receive Signal Strength Indicator**

Receive Signal Strength Indicator (RSSI) is a direct measure of the strength of the incoming received signal. The RSSI value does not though provide any indication as to the quality of the received signal nor if the signal is being transmitted from the desired source. The RSSI value can be either sampled internally by the sensor module or externally by an analog to digital converter. The RSSI value is then encoded to an appropriate scale. The ZIGBEE module automatically encodes the RSSI value to a dBm scale. This is abbreviated notation for decibels of power relative to a 1 mW reference signal. An RSSI value of 0 dBm would be equivalent to the 1 mW reference. The RSSI value is calculated as 10 times the log of the ratio of power received to the 1 mW power reference.

**Link Quality Indicator (LQI)**

The Link Quality Indicator is another parameter used to quantify the performance of wireless systems. The ZIGBEE wireless module used during this project did provide an LQI output which ranged from 255 to 0. Unfortunately, no documentation was provided as to how the LQI was calculated and thus it must be analyzed on a generic scale. This severely limits the ability to compare LQI values among various wireless sensors, because they are each based on proprietary calculations.
**Signal to Noise Ratio**

Signal to Noise Ratio (SNR) is a common parameter used to measure wireless transmission performance. As its definition indicates, it is calculated as the ratio of desired signal to the undesired noise signal. This noise content can be induced by other devices operating in a similar frequency band. Although the SNR is an excellent indicator of signal quality, it cannot be used to directly measure the path loss within a specific environment. It is only used when evaluating the entire wireless network and quantifying interference from surrounding systems.

**Message Error Rate**

The Message Error Rate (MER) is calculated as the ratio of non-received messages to transmitted messages over a finite time window. This test is conducted by programming a set transmission frequency at the transmitter and recording all received messages at the receiver. After a sufficient logging window, the MER value can be calculated. The advantage of MER data is that it truly represents the performance of wireless networks by providing a metric that relates to transmission capacity rather than the quality of the transmission link.

**Selection of Wireless Quality Parameter**

For this study, both the RSSI and MER values were used to quantify wireless performance. RSSI was used extensively to empirically represent the path loss through individual environmental factors. Since RSSI was a standardized measure referenced to a 1 mW transmission reference, the resulting values are easily compared to RSSI values of other wireless sensors. Furthermore, being in units of
dBm, the RSSI value can be used to verify path loss estimates established by theoretical path loss performance laws. MER will be used at the conclusion of the study to verify the performance of a full network when installed in an optimized pattern defined by the RSSI empirical performance model.

5.3.5. **Experimental Design for Measurement of Wireless Signal Transmission Performance**

**Identification of Test Factors and Treatment Levels**

Many physical factors within a CAFO will cause attenuation in wireless signals and limit the performance of wireless sensor networks. The majority are physical obstructions such as animal cages and structural steel and concrete. Others are natural attenuators such as free space and animals which absorb the electromagnetic energy. For a poultry layer operation, the following factors and treatment levels were identified and served as the focus of this research.

- **Separation Distance:** The distance between the transmitter and receiver will be separated by up to 56 meters to validate the free space path loss model. All other factors will be tested in conjunction with this test to identify any interaction between separation distance and other path loss factors.

- **Cage Separation:** The transmitter and receivers will be placed 0, 1, 2, and 3 cages apart. Each cage separation will represent a new mode of path loss. This test will be conducted under all separation distance treatment levels.

- **Concrete Separation:** A high rise layer facility will be tested with the transmitter on the upper level and the receiver on the lower level. Performance
will be quantified for concrete separation versus all treatment levels of separation distance and cage separation.

- **Antenna Plane Orientation**: The chip antenna will be tested in both a horizontal and vertical plane orientation. The horizontal orientation will align the y-z antenna plane with in parallel with the CAFO floor. The vertical orientation will align the x-z antenna plane in parallel with the CAFO floor.

- **Antenna Angular Orientation**: The angular orientation of the antenna will be evaluated in both treatment levels of the antenna plane orientation. This will be conducted at static locations.

- **Transmitter and Receiver Height**: The transmitter and receiver will be tested at heights equivalent to the lowest, middle, and highest animal cage in a high rise poultry layer facility. Interaction of height will be tested for both low and high conditions.

- **Animal Absorption**: Cage separation testing will be repeated to quantify the amount of path loss associated with the animals. A direct comparison of results between full density and no animal density will yield the animal absorption affect.

**DETERMINATION OF SAMPLING SIZE**

The sampling size of path loss data was designed to maintain the confidence interval within an acceptable level, given the high fast fading and thus high variance of results characteristic of path loss in CAFO environments. A preliminary study on the temporal distribution of RSSI values within a CAFO was conducted. The results
provided an estimate for the standard deviation of RSSI values and were used to select an appropriate sampling size.

RSSI data was collected continuously from a transmitter, receiver pair to determine the magnitude of change in the signal strength over time. In order to prevent biasing caused by other sources of electromagnetic noise, the test was conducted with the receiver and transmitter isolated in an open air, free space environment. An RSSI value was recorded every 2 seconds and a total of 2743 data points were collected (Figure 46). The histogram of this test shows a very consistent response of signal strength over time, with a median RSSI of -66 dB and a standard deviation of 1.1 dB. This low standard deviation indicates that very little fast fading was present when the receivers and transmitters are located in an isolated, open air environment. This was expected since the main cause of fast fading is the presence of multipath interference which is both volatile in nature and unpredictable over time.
Figure 46. Statistical summary for temporal signal strength variation in open air free space environment.

Further variance tests were conducted inside a CAFO facility to determine the effect of fading within this specialized environment. The transmitter and receiver were located at a position with one aisle and 25 linear feet of separation between them. The results of this test indicated a significantly higher level of variance. The standard deviation increased from a value of 1.1 dB for the zero aisle separation to 3.9 dB for one aisle of separation (Figure 47). The higher variability in signal strength under static measurement conditions indicates that the environment does in fact induce fast fading or multipath errors. The source of such multipath interference was the summation of wave components in a multi-ray field. As the wireless signal radiates from the transmitter source, some of the energy travels...
directly to the receiver through small line or sight paths. Other components of the transmitted energy reflect off the many surfaces of a CAFO and cause fading or an attenuation of the direct signal. The magnitude of fading was not constant, but rather random and dependent on the individual reflection of each signal. This randomness resulted in higher variability in the signal strength measurement between two points with strong fading characteristics. Other types of path loss such as absorption or total reflection continuously impact the magnitude of signal strength rather than affecting the variation between sequential measurements and thus will not impact the fast fading component of the signal.

Figure 47. Statistical summary for temporal signal strength variation in a poultry layer house with 1 aisle and 25 linear feet separation.
Based on this knowledge of fast fading and high standard deviation values for aisle separated readings, a sampling point scheme was designed to maintain the uncertainty of measurement less than ±1.5 dB. The true mean of a sampled value can be estimated with greater accuracy by increasing the number of samples collected during the particular trial. If a preliminary data set was available which provided an estimate of the standard deviation of the measured value, then a desired confidence interval width can be chosen by solving for the required number of samples. The actual mean of subsequent trials will be calculated as the measured mean ± the desired uncertainty interval. The width of a confidence interval is known to be (Equation 30):

\[
Range \ of \ CI = \pm z_{0.95} \cdot \frac{\sigma_x}{\sqrt{N - 1}} = 1.5 \, dB
\]

Equation 30. Calculation of sample size to control confidence interval width for mean RSSI measurement (Derived by Author).

By choosing a desired uncertainty interval of 1.5 dB, the confidence interval solution resulted in a critical sample size of 27 points. To ensure a factor of safety regarding the prediction of the standard deviation, a sample size of 30 signal points was chosen as the desired size for all path loss evaluation trials.

5.4. RESULTS AND DISCUSSION

Testing was conducted to evaluate the effect of each of the treatment factors highlighted in the experimental design. The presentation of these results will group
the findings into three distinct categories. The first group presented will include those attenuation factors which are specific to the test fixture rather than the CAFO facility. These include orientation of the test node antenna, path loss through the test node plastic enclosure, and natural path loss through a free space environment. The second group of parameters includes those which exhibit a major impact on the path loss within a CAFO facility. These include path loss from increased transmission distance and transmission through cages. The final results will focus on path loss factors that do exhibit significant signal attenuation, but either have less magnitude of attenuation or have a classified response based on the physical environment. These include path loss from changes in antenna height, diffraction off the floor surface, and transmission through a concrete floor.

5.4.1. Empirical Results for Quantifying Wireless Sensor Data Transmission Performance

Confirmation of Free Space Path Loss Model

The Friis’ model for free space path loss was derived based on the specific attributes of the wireless nodes used during this work to yield a theoretical path loss performance as a function of transmission distance in meters (Equation 25).

\[
\frac{P}{P_i} (dB) = -\frac{40.23}{20\log[r]}
\]

The regression model for path loss without a plastic enclosure can be used to validate this theoretical performance model (Figure 48). Based on the regression analysis, the empirical path loss model was:
\[ \frac{P_r}{P_i} (dB) = -46.31 - 20.86 \log[r] \]

Figure 48. Regression model for path loss based on experimental RSSI data collected under free space conditions.

A 15.7% difference in the offset estimation and a 4.3% difference in the slope estimation were found between the theoretical and experimental performance. By applying a 95% confidence interval for the estimates of slope and offset, a range for the regression model was found to be:

\[ \frac{P_r}{P_i} (dB) = -(45.3 , 47.3) - (20.2 , 21.6) \log[r] \]
Even after consideration of the confidence interval for both the slope and offset, modest deviations still exist between the theoretical and experimental curves. The slope deviation has the smallest magnitude and can most likely be explained by closely examining the environment of the wireless node. In the theoretical calculation it was assumed that the wireless transmitter was located in free space. In reality, the wireless module was directly attached to a circuit board which extended past the edge of the antenna by $\frac{1}{2}$". Although small, this presented an additional media source for the wireless signal to travel through and thus would exhibit a slight increase in signal attenuation. The manufacturer of the circuit board used in this project estimates the dielectric constant to be 4.3.

The error associated with offset prediction is larger in scale, but again reasonable assumptions can be made as to its source. The offset parameter for the theoretical performance was based on the antenna gain and transmission wavelength. The original calculation was based on the stated directional gain from the antenna datasheet. Small estimation errors in this directional gain would overall errors in predicting system response. It was calculated that an estimation error of -2.54 dBi for the antenna gain would sufficiently bias the offset parameter (Equation 31).
\[
\frac{Pr}{Pt} (dB) = 10 \log \left( Gt \times Gr \frac{\lambda \times \lambda}{16 \times \pi \times \pi} \right) = -40.23
\]

\[
\frac{Pr}{Pt} (dB) = 10 \log \left( [Gt + \Delta] \times [Gr + \Delta] \frac{\lambda \times \lambda}{16 \times \pi \times \pi} \right) = -45.3
\]

\[
Gt + \Delta = 0.557
\]

\[
(Gt + \Delta)_{dBi} = 10 \log 0.557 = -2.54
\]

Equation 31. Calculation of true antenna gain estimation for valid free space path loss model (Derived by Author).

A secondary review of the antenna manual indicated that a directional gain of -2.54 dBi was within the expected limits of possible values. This was especially the case for the XY plane which was used primarily to conduct the free space verification testing.

**IMPACT OF ANTENNA ORIENTATION ON SIGNAL STRENGTH**

Antenna orientation also played a critical role in determining the performance of a wireless sensor. In an ideal wireless mesh network system, the antenna would provide an isotropic response and would radiate energy equally in all directions. In reality, no antenna design will provide a true isotropic response and antenna orientation will always play a key role in determining the overall performance of a wireless system. The base antenna used for the duration of this study was a Rufa 2.4 GHz SMD Antenna. Both the transmitter and receiver were fitted with identical antennas. The antenna datasheet provided detailed radiation
patterns for all three axis of the antenna (Figure 49). These results show this antenna to be nearly omnidirectional in all planes.

![Diagram showing radiation patterns for all three axes](image)

**Figure 49. Zigbee surface mount antenna radiation pattern.** Reprinted from Figure 7.3 in Rufa 2.4 GHz SMD Antenna Datasheet, Antenova.

Testing was still required to determine the overall affect of receiver/transmitter orientation because of the additional directionality asserted by the housing, wiring harness and mounting system of the wireless sensor nodes. Orientation trials were conducted by positioning the receiver and transmitter in stationary positions located 15 meters apart with no aisle separation (Treatment 4). After 30 signal strength points were recorded, the receiver was rotated by 45°. As a series of 45° rotations were conducted until the antenna was again located in line with the transmitter. Results showed that the wiring harness, which blocked a line of sight transmission at the 180° orientation, did provide the largest impact to signal strength (Figure 50). Additional conclusions were that less attenuation existed when the receiver was aligned perpendicular to the transmitter.
A secondary trial was completed to determine if aisle separation had any interaction on the orientation performance of the antennas. For this trial (Treatment 4) the receiver and transmitter were separated by 7 linear meters and one aisle. Results yielded the same general trend in orientation performance, albeit at a much lower signal magnitude due to the loss through the single cage.

Figure 50. Angular antenna position impact on signal strength based on experimental RSSI values.

It can be argued that a chip type antenna would not be optimal for a CAFO environment and rather a half wave whip antenna, which provides a more omni-directional response with typically higher efficiencies, would be preferred. The
disadvantage of a whip style antenna was the connection between the sensor node and the antenna. Any connections external to the sealed node casing will provide an access point for ammonia laden air to enter. This contaminated air will quickly corrode the electrical connections on the sensor board and will cause the overall failure of the node. For these reasons it was desired to test a fully enclosed sensor node with a chip type, embeddable antenna.

Applications of these results can be compared to higher gain antennas, assuming that the true antenna gain is known. The results from the ZIGBEE module are with respect to the 0 dBi chip antenna gain. A higher gain antenna would simply reduce the overall path loss by the specified gain (in dB) at a particular orientation. If the receiver also employed a high gain antenna, its magnitude would also be added to the experimental attenuation values to reduce the overall path loss.

A secondary orientation effect was expressed by the vertical orientation of the sensor rotating around its z-axis. A trial was conducted to differentiate the performance of the sensor in the two possible mounting positions, horizontal and vertical. Results showed improved performance when aligned in the vertical manner (Figure 51). This performance difference can be directly attributed to the antenna properties which document significantly higher gains in the XY plane than in the YZ plane.
Figure 51. Comparison of signal strength versus transmission distance for vertically and horizontally mounted wireless nodes within a single poultry aisle way.

**IMPACT OF PLASTIC ENCLOSURE ON SIGNAL STRENGTH**

A sealed plastic enclosure was used to protect the wireless nodes from the harsh environment present in CAFO facilities. In particular, the sealed housing prevented the sensor circuit board from being exposed to potentially high levels of ammonia and hydrogen sulfide which can cause corrosion on the circuit board. The negative aspect of a sealed enclosure though was an immediate increase in path loss. Most plastic materials have a relative dielectric constant of 2 – 3, indicating that they are 2 – 3 times less able to allow electromagnetic energy to pass through. Although significant, this is much lower than steel or other metallic enclosures. On a decibel
scale, this negative gain will represent an increased path loss of 3 dB – 4.8 dB, again depending on the exact material makeup of the enclosure.

Experimental testing was conducted to determine the magnitude of attenuation caused by the enclosures used for this project. The transmitter and receiver were aligned facing each other and a series of path loss values were recorded at 10 foot intervals with and without the plastic enclosure present.

Analysis was conducted by averaging the path loss at each measurement point for 100 feet of observations. The 100 feet interval was used as a breakpoint because both response curves converge towards the maximum attenuation of -90 dB shortly after this threshold. The average path loss with covers was then subtracted from the average path loss without covers for each measurement point to attain a direct measurement of path loss from the presence of a plastic enclosure. The results indicated a mean path loss of 3.45 dB associated with the plastic enclosures. The 95% confidence interval for this mean spanned from 2.09 to 4.82 dB. The mean value of 3.45 dB fell well within the predicted range of 2.09 to 4.8 dB for plastics.
Figure 52. Statistical summary of path loss differences associated with plastic enclosure.

Improvements in this path loss characteristic could be achieved by modifying the material used to enclose the wireless node. As discussed previously, the attenuation of an enclosure was directly related to its relative dielectric constant. The dielectric constant or dielectric permittivity of a material describes its ability to become internally polarized when subjected to an electric field. The units of the absolute dielectric value are F/m. Higher dielectric constants then indicate that the medium has a higher capacitance (Farad) rating than free air. This higher capacitance creates a poor wireless environment, because less energy is propagated through the system. Unfortunately, few materials offer better dielectric constant parameters than the current enclosure. Teflon, with a dielectric constant of 2.1,
would be a possible substitute for the current plastic housing. Negatives of Teflon would include a reduced material hardness as well as an increased enclosure cost.

A more drastic alternative would be to no longer fully enclose the antenna. Again, remotely attached antennas would provide an entry point for moisture, corrosive gasses, and dust, but if properly sealed, would provide increased signal performance. Another option would be to fully encapsulate the entire wireless sensor node with a potting compound, except for the antenna. This encapsulation would protect the circuit board components from corrosion while still minimizing antenna attenuation.

**Impact of Linear Distance within an Aisle Way on Signal Strength**

Based on the Friis equation of path loss over distance, it was known that signal strength will decrease as the transmitter and receiver are separated by a finite distance in open space. In one dimension, the path loss along an aisle way or corridor should closely follow the free space model. Previous research had shown that wireless systems used in hallway or corridor environments could act similar to horn antenna and provide a waveguide which would amplify the signal strength relative to a traditional free space response. Under these conditions, the walls of the corridor do not exert excessive reflection which would cause multipath errors, but rather channel the electromagnetic energy down a common path. Poultry aisles are significantly different from hallways though in that they have exposed metal walls rather than drywall which will lead to increased signal reflection and they have a non-uniform or jagged surface which will cause a random incident angle. In doing
so, it is hypothesized that poultry aisle ways will exhibit a significant amount of multipath error caused by the random reflections off the cage walls. It is further hypothesized that this negative multipath error will be greater in magnitude than the positive waveguide effect and the overall signal strength will be less than that observed in free air studies.

To test this theory in a poultry facility, a transmitter and receiver were located at set distances apart and the signal strength between the two entities was measured. A minimum of 30 samples was taken at each position. Each sampling location was separated by 4.6 feet. The antennas on the transmitter and receiver were both maintained planar to each other and were oriented in the XY plane. This test was repeated for three separate trials to determine the effect of aisle ways on performance and the variability in aisle way performance over time.

The first trial was conducted on April 19th, 2007. As with the baseline performance data, a log based regression analysis was conducted to yield a correlation function in the form of $\text{RSSI} = -A - N \cdot \log_{10}(\text{Distance})$. The output of the regression analysis yielded an N value of 2.6 with an $R^2$ value of 0.75 (Figure 53). This indicated that the path loss was greater than free space and that the waveguide effect of the cages was not great enough to overcome the multipath losses associated with the non-uniform cage edges. The 95% confidence interval for N provided a range of 2.49 to 2.81 (Equation 32).
Figure 53. Regression analysis for path loss within a single aisle on April 19th.

Range of slope:

\[
b_i \pm t \left( \frac{1 - \alpha}{2}; n - 2 \right) s\{b_i\} \\
\Rightarrow -26.5 \pm 1.96\{0.8166\} = (-24.90, -28.10)
\]

Equation 32. Confidence interval for regression parameters from April 19th aisle path loss test (Calculated by Author).

The second trial was conducted on April 27th, 2007. The regression analysis was repeated to compare the response of the signal strength over the two measurement periods. The results of the regression model yielded an N value of 2.74, again greater than the free space regression slope and very similar to the
results from the original trial (Figure 54). The confidence interval for the slope was 2.69 to 2.75 which overlaps with the confidence interval from the first trial and indicates that the two trials were statistically similar and that no temporal variations occurred (Equation 33).

![Figure 54. Regression analysis for path loss within a single aisle on April 27th.](image)
Range of slope:

\[
b_j \pm t \left( \frac{1 - \frac{\alpha}{2}}{n - 2} \right) s \{ b_i \}
\]

\[
\Rightarrow -27.4 \pm 1.96(0.2287) = (-26.95, -27.84)
\]

Equation 33. Confidence interval for regression parameters from April 27th aisle path loss test (Calculated by Author).

The final trial was conducted on June 11th, 2007. A regression model was again applied to the data and results in an N value of 2.37 (Figure 55). This again was greater than the path loss expected for free space, but much less than the N value calculated in the previous 2 trials. The 95% confidence interval for N was 2.30 to 2.44 (Equation 34). This confidence interval did not overlap with the previous studies and indicated that some variability exists in the estimation of the performance slope.
Figure 55. Regression analysis for path loss within a single aisle on June 11th.

Range of slope:

\[ b_i \pm t \left( \frac{1 - \frac{\alpha}{2}}{n - 2} \right) s \{b_i\} \]

\[ \Rightarrow -23.7 \pm 1.96 \{0.3727\} = (-22.96, -24.43) \]

Equation 34. Confidence interval for regression parameters from June 11th aisle path loss test (Calculated by Author).

<table>
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<tr>
<th>Date</th>
<th>Max N</th>
<th>Min N</th>
<th>Significance</th>
</tr>
</thead>
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<td>-2.490</td>
<td>-2.810</td>
<td>a</td>
</tr>
<tr>
<td>4/27/2007</td>
<td>-2.695</td>
<td>-2.784</td>
<td>a</td>
</tr>
<tr>
<td>6/11/2007</td>
<td>-2.296</td>
<td>-2.443</td>
<td>b</td>
</tr>
</tbody>
</table>

Table 10. Summary of single slope model N values for three separate data collection periods.
Although the slope of the regression lines were not all significantly similar, that alone does provide enough justification to declare the regression curves dissimilar (Table 10). When considering log_{10} based models, a change in the offset of the equation can exhibit a very similar response to a slight change in the slope of the regression line. As a plot of all three regression lines shows, the April 19\textsuperscript{th} and June 11\textsuperscript{th} data set look much more similar than when compared to the April 27\textsuperscript{th} dataset, but statistically the slope of the June 11\textsuperscript{th} set is different (Figure 56).

![Figure 56. Graphical comparison of three regression models for estimating path loss within a single aisle.](image)
All three models were then combined by averaging the regression fits at 5 foot intervals. The raw datasets were not used to develop an overall regression model because each dataset has a significantly different number of samples. If the raw data was used, the output regression would be biased by the trials which contained the highest number of samples. The output of the averaged regression models yielded an offset of -27.83 dB and a slope of -25.83 (Figure 57). This results in an N value of 2.58.

![Regression Model](image)

Figure 57. Cumulative regression results for average of three separate sampling periods to predict path loss through a single aisle way in a poultry layer facility.

**IMPACT OF ANIMAL CAGES ON SIGNAL STRENGTH**

A test procedure was developed to accurately quantify the path loss caused by wireless transmission through an animal cage. This test aligned the transmitter
and receiver directly across from each other at a given cage separation. Data was collected over a range of 100 feet within the layer house, but the transmitter was moved each time with the receiver. By moving both elements, the impact of cage separation and the variability in path loss over different portions of the building were quantified.

To monitor path loss, the transmitter and receiver were both placed at a height of 6 feet above the floor level. Results indicate that the average path loss across a single, fully stocked cage was -72.7 dB with a 95% confidence interval width of only 0.83 dB (Figure 58). The linear distance between the transmitter and receiver during this test was 2.26 m. The predicted free space path loss for a separation distance of 2.26 m was -50.2 dB based on experimental measurements at this distance. This resulted in a single cage effect path loss of -22.5 dB.

These results were compared to an identical test conducted in a facility with an identical set of cages, but with no animals present. For this test, the average path loss was found to be -60.9 dB (Figure 59). This resulted in a -11.8 dB additional path loss directly caused by the presence of animals in the cages. This was a very significant value, but also not unexpected given the tight stocking density of caged layer birds and the high propensity for the birds to absorb and reflect electromagnetic energy. Birds are composed of nearly 75% water and water is a poor conductor of electromagnetic waves (dielectric constant = 80). Based on these conditions, it was expected that birds as well would be poor conductors.
Figure 58. Interval plot and statistical summary of RSSI values for repeated measurements across a single fully stocked cage.
Figure 59. Interval plot and statistical summary of path loss values for repeated measurements across a single empty cage.

This comparison test was repeated for birds and no birds with two cage aisles of separation. Results showed the empty facility to have a two cages path loss of -74.8 dB while the fully stocked facility had a path loss of -82.8 dB (Figure 60 &
Figure 61. This is in comparison to the predicted path loss of 57.9 dB for a similar transmission distance in free air. Less significance is seen from the animals because of the large impact of multiple cage rows. The stocked caged yielded a 24.9 dB loss while the empty cages yielded a 16.9 dB loss. The loss associated with birds can then be calculated as 8 dB for a 2 cage system.

Figure 60. Statistical summary of path loss values for repeated measurements across two empty cages.
**Figure 61.** Statistical summary of path loss values for repeated measurements across two fully stocked cages.

### IMPACT OF ELEVATED ANTENNA ON FREE SPACE PATH LOSS

The previous path loss procedure was conducted with the wireless sensor placed 6 feet off the floor level which equated to the center height of the poultry cages. The height of the antenna was used as a treatment to determine if an elevated antenna would present a reduced path loss. The hypothesis was that when the antenna was placed at the center height of the cage, path loss was developed by both the free space path loss phenomena and other path loss components associated with reflection of signal by the cages.

A telescoping fixture was designed and fabricated to allow the wireless nodes to be placed at a height of 13 feet which was just greater than the overall height of the cages.
the animal cages. The same procedure was used to monitor the path loss by measuring the RSSI value between the sending and transmitting node (Figure 62). The results of this test were analyzed by performing a regression of the log of the separation distance against the RSSI value.

\[
\text{RSSI (dB)} = -33.86 - 24.17 \log_{10}(\text{Distance (ft)})
\]

![Figure 62. Regression results for wireless sensor path loss when elevated to 13 ft above the floor surface and within a single aisle.](image)

The results of this regression analysis proved the original hypothesis wrong and concluded that the single axis free space path loss was actually decreased by elevating the antennas above the animal cages. A secondary evaluation of the area above the top of the animal cages reveals the assumption of free space was wrong. Only 3 feet of space exists in many areas between the top of the cages and the
bottom of the ceiling. Furthermore, a structural steel spanning truss is fixed every
thirty feet and protrudes down from the ceiling, again causing additional
disturbances to the signal strength.

Although increased strength can be achieved by placing nodes within cage
aisle, elevated antennas exhibit much greater performance when cross row
transmissions were considered. When elevated, the sensors provided the same
power output with little influence of angular orientation. The only additional
attenuation occurs from the non-isotropic gain orientation of the antenna.

**IMPACT OF LOWERED ANTENNA ON FREE SPACE PATH LOSS**

Theoretical models have shown that the proximity of a wireless transmitter
to the floor surface can cause additional wireless signal attenuation. This
attenuation results from an increase in signal reflection off the floor surface with a
small phase lag difference between the reflected wave and the line of sight wave.
The small phase lag results in an incident wave that has a negative cumulative effect
at the receiver. As the receiver and transmitter were located closer to the ground
surface, angle of wave incidence increases greatly and the grazing angle tends
towards zero. This tendency towards small grazing angles also creates a tendency
for the coefficient of reflection to tend towards -1, yielding the maximum negative
reflection effect (Equation 35).
\[
\lim_{\alpha \to 0} \Gamma = \lim_{\alpha \to 0} \frac{\epsilon \sin(\alpha) - \sqrt{(\epsilon - \cos^2 \alpha)}}{\epsilon \sin(\alpha) + \sqrt{(\epsilon - \cos^2 \alpha)}} = -1
\]

Equation 35. Calculation of limit of the coefficient of reflection as the grazing angle approaches zero (Bansal, 2004).

To verify the results of the predictive model, a test was conducted to analyze the transmission loss of a receiver transmitter pair located near the floor of a CAFO. Both the transmitter and receiver were placed at a height of 0.25 meters above the floor surface and the receiver was continuously moved away from the transmitter to evaluate the signal attenuation over the length of the facility. A regression analysis of this test resulted in the following regression equation:

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
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</thead>
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<td>0.7529</td>
<td>-62.12</td>
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<td>Log Distance</td>
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<td>0.3983</td>
<td>-43.03</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Figure 63. Regression analysis output for path loss versus the log of transmission distance when transmitter and receiver were located 0.25 m above the floor surface.
When compared with the standard regression equation for path loss within a single aisle way, we see that significant differences in the predictions do exist (Figure 64).

![Comparison of reflection model to standard path loss model](image)

Figure 64. Comparison of reflection model to standard path loss model.

To test the accuracy of the predictor model, the model results were plotted versus the experimental results. Since the model was only accurate when $r >> 5 h_h_r$ only distance values greater than this threshold were plotted. The results yielded an $R^2$ of 0.999 between the predicted reflection path loss and the true path loss (Figure
The slope of the regression line deviated from 1 slightly, which indicates that the predicted value did not provide a direct representation of the true value. Due to the high $R^2$ correlation though, the prediction model can be modified to include an adjustment factor based on the magnitude of the prediction value (Equation 36). By adding the second prediction term, the reflection model was an accurate estimation for the path loss caused by placing the sensor and receiver in near proximity to the floor surface of a CAFO.

Figure 65. Probability plot of predicted versus true RSSI values for floor reflection model within a single aisle way.
The final form of the reflection model then becomes:

\[ RSSI_{Floor} = 0.86 (\cdot 46.8 - 17.1 \log \text{Distance}) - 9.70 \]

Equation 36. Corrected model for floor reflection path loss in poultry layer house with 0.25 m sensor heights (Calculated by Author).

**IMPACT SIGNAL DIFFRACTION AND VERIFICATION OF DIFFRACTION MODEL**

A test was designed to verify the theoretical path loss caused by diffraction. The wireless sensors were located 0.1 m below the top edge of the cages and again both the transmitter and receiver were moved together simultaneously. Results showed an average path loss of -60.0 dB across the top of a single cage (Figure 66). Previous free space models revealed an expected path loss of -50.2 dB for the same transmission distance. The diffraction of electromagnetic energy across the top of the cages has added an additional -10.2 dB path loss. This was quite comparable to the estimated diffraction path loss of -10.4 dB. One explanation for this discrepancy was that the cage surface is not truly a knife edge surface and the actual amount of diffraction is less than the theoretical maximum case.
Figure 66. Statistical summary of path loss values for measurement of diffraction across the top edge of two cages.

**IMPACT OF CONCRETE FLOOR ON SIGNAL STRENGTH**

Typical for many high rise or retrofitted belt battery barn, the test facility had a concrete floor structure which separated the upper and lower levels. Concrete is widely known to cause significant wireless signal attenuation, but is also known to have great variation in its attenuation impact. Depending on the formulation of the concrete, the thickness of the concrete, and the amount of reinforcement steel used; the attenuation levels will vary greatly. In the barns studied for this project, no steel reinforcement was included, but the concrete was installed in a modular way and did have varying cross sections throughout the length of the buildings. The signal attenuation increased proportionally to the increase in cross section.
To study the affect of concrete floors on wireless signal attenuation, a wireless transmitter was placed on the upper level of the CAFO building and a receiver was placed on the lower level. Tests to monitor the effect of separation distance and cage separation were conducted. Results showed high levels of attenuation caused by the concrete separation.

\[
\text{RSSI (dB)} = -56.26 - 15.29 \log_{10}(\text{Separation Distance (ft)})
\]

A comparison of the regression models for concrete separation versus no concrete reveals an additional attenuation of \(-17.87 + 5.61 \log_{10}(\text{r (meters)})\) associated with the presence of concrete. This was significant when compared to other modes of attenuation and will severely limit the expansion of wireless network in multilevel
buildings. Furthermore, due to the non-constant cross sectional structure of the concrete, the variability in concrete path loss was greater. Without making significant adjustments in the compositional makeup of the concrete, little can be done to improve path loss through these structural obstructions. In networks which allow for multi-hopping, networks can be designed so that two nodes are placed in close proximity on opposite sides of the obstruction and provide a corridor for data transfer. The negative impact of this design is that the network now has a critical path in which if either node fails, the overall data transfer through the network will cease.

5.4.2. A 2D Signal Attenuation Model on Signal Strength in a Poultry Layer Facility

Selection of Variables for Two Dimensional Model

Many factors have been determined to affect the distribution of signal strength within a CAFO. In particular, the experimental results show spatial distribution was most strongly affected by the transmission distance and cage separation for a single floor facility. In order to better calculate the optimal node spacing for wireless communication inside a CAFO, a spatial distribution model, based only on transmission distance and cage separation factors, was developed to predict the signal strength at any given point inside the building.

Other factors were considered for inclusion in this prediction model, but were determined to be undesirable for a variety of reasons. The antenna orientation will certainly impact the path loss and thus the model results, but this factor was not
realistically controllable with a full scale network deployment and was thus deemed a random variable which would only increase the uncertainty of the model. Wireless network designers must take this fact into consideration during the network design phase and ensure that the node antenna will present reasonably isotropic gain characteristics.

The enclosure design and material properties will also impact path loss, but will do so in a static way. If the material properties are known, the final model output can be either increased or decreased based on the material attenuation. Antenna height also exhibited a significant path loss effect and did warrant consideration in the two-dimensional model. It was decided though that the data sampling requirements for inclusion of node height as a factor were too great for the scope of this study, thus the model presented in this work was only valid for wireless node response when located at the height of the center cage in a poultry layer facility. Based on the verified surface reflection model, an estimate for antenna height could be included for future applications of this prediction model, but this implementation should be done on a case-by-case basis rather than broadly across all building designs.

Concrete floor separations or other structural separations would also impact the accuracy of the model, but were such a significant impact that it was decided that these conditions should be considered as an entirely separate model. Furthermore, in most applications, a network corridor will allow data transfer through multiple levels of CAFO buildings, with the majority of nodes within a single level operating as a cohesive network where the current predictive model will
adequately service. Finally, system based parameters such as operating frequency would also bias the accuracy of this predictor model, so it must be noted that this model was limited to the response of 2.4 GHz systems only and that further work would be required to adapt this work to alternative network frequencies.

**Spatial Distribution of Signal Strength in a Poultry Layer Facility**

A two dimensional survey of signal strength was conducted by placing a stationary transmitter in the center of a poultry belt battery layer house (Figure 68). The receiver was moved at 4.5 foot increments away from the transmitter and 30 RSSI measurements were taken at each point. This was repeated for 0, 1, 2, and 3 cage aisle separations. A regression analysis was conducted to relate the signal strength throughout the building to the linear distance and aisle separation value.

<table>
<thead>
<tr>
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<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
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<td>0.000</td>
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<td>-11.73</td>
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<td>Log Dist</td>
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<td>0.000</td>
</tr>
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<td>S = 5.23098</td>
<td>R-Sq = 68.8%</td>
<td>R-Sq(adj) = 68.0%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The R² value of 0.68 was quite respectable given the dynamic nature of an indoor CAFO wireless attenuation environment. This indicates that nearly 68% of the variation in the results was explained by the model. The other 32% of variation were due to other factors not included in the prediction parameters and random variation caused by localized fast fading within the physical layout of the barn. The p-values were all less than 0.000, indicating a high level of significance in the factors for offset, row separation, and log of separation distance.

A scatterplot of the model residuals versus transmission distance shows the residuals to be evenly distributed around zero (Figure 69). This was a good
indicator that the chosen model was appropriate. The magnitude of variation in the residuals was much higher at lower distance levels. This was explained by the trend of RSSI values at extremely small distances to converge asymptotically towards zero signal loss. The model does a poor job of predicting results at these levels below the smallest measurement point of 4.5 feet. The raw data also converges towards -90 as the distance increases. This occurs because the maximum sensitivity of the ZIGBEE module is -90 dB. Any values with a path loss greater than this value will not be validated and thus no RSSI value will be available. This also causes the model to converge towards a slope of zero and a magnitude of -90 as the distance transmission distance increases.
The scatterplot of residuals versus row separation did show signs of non-normality, as the residuals were not normally distributed around a mean residual of zero (Figure 70). This result can be expected based on the prior results of signal attenuation through cages. It was found that a non-linear response existed between one and multiple cage separations.
In order to correct for the non-normality associated with path loss across aisles and to improve the overall relationship between path loss and the spatial location of sensors, the regression analysis was modified to include a second order aisle loss term. The result yielded an $R^2$ value of 0.796, reducing the uncertainty of the model by 11.6%. Again, all P-values were less than 0.000, indicating that all terms were significant (Figure 71).
Regression Analysis: B3 RSSI versus Log Distance and Aisle Separation, and Aisle Separation Squared

The regression equation is: B3 RSSI = -43.2 – 16.2 Aisle + 3.30 Aisle^2 - 18.0 Log(Dist)

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-43.184</td>
<td>2.489</td>
<td>-17.35</td>
<td>0.000</td>
</tr>
<tr>
<td>All Aisle</td>
<td>-1.6184</td>
<td>0.1424</td>
<td>-11.36</td>
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</tr>
<tr>
<td>Aisle^2</td>
<td>3.3019</td>
<td>0.4885</td>
<td>6.76</td>
<td>0.000</td>
</tr>
<tr>
<td>Log Dist</td>
<td>-18.008</td>
<td>1.321</td>
<td>-13.64</td>
<td>0.000</td>
</tr>
<tr>
<td>S = 4.18071</td>
<td></td>
<td>R-Sq = 80.3%</td>
<td>R-Sq(adj) = 79.6%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 71. Regression analysis results for 2D spatial model with second order aisle term included.

Analysis of the residuals for the modified regression model yields a confidence interval with of ±0.9014 dB (Figure 72).
### Figure 72. Statistical summary of prediction model residuals after the addition of a second order aisle separation term.

The addition of the second order aisle separation term also improved the normality of the residuals with respect to the aisle separation (Figure 73).
A matrix plot of the predictor and response variables does highlight one remaining issue with the model. There remained a slightly linear relationship between the log of the separation distance and the aisle separation term. This could potentially be caused by an interaction between the two terms. In order to test for interaction, the combination of aisle separation and log of distance were added to the model and the residuals were again evaluated for improvement.
Figure 74. Matrix plot of Barn 3 path loss model input and residual terms.

The addition of the aisle separation and log of distance product as a predictor for the path loss again increased the R^2 value to 0.86 and has reduced the confidence interval of the residuals. Furthermore, the P value for all model terms was less than 0.000, which indicates that all factors are significant at a level less than 0.0005. This confirmed the previous hypothesis that there was a visual interaction between the aisle separation and the log of distance. The confidence interval for the residuals has now been reduced to ±0.741 and a new matrix plot of response and predictor does not yield any additional concerns regarding non-normality or variable interaction (Figure 76).
Regression Analysis: B3 RSSI versus Log Distance and
Aisle Separation, Aisle Separation Squared, and Aisle/Log Distance Interaction

The regression equation is: B3 RSSI = - 32.9 - 28.5 Aisle
+ 4.19 Aisle^2 - 23.7 Log(Dist) + 6.58 Aisle x Log(Dist)

<table>
<thead>
<tr>
<th>Predictor</th>
<th>Coef</th>
<th>SE Coef</th>
<th>T</th>
<th>P</th>
</tr>
</thead>
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<td>-12.34</td>
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<td>0.4302</td>
<td>9.74</td>
<td>0.000</td>
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<td>1.444</td>
<td>-16.44</td>
<td>0.000</td>
</tr>
<tr>
<td>Aisle x Log Dist</td>
<td>0.6582</td>
<td>0.1085</td>
<td>6.07</td>
<td>0.000</td>
</tr>
<tr>
<td>S = 3.46103</td>
<td>R-Sq = 86.7%</td>
<td>R-Sq(adj) = 86.0%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 75. Regression analysis results for 2D spatial model with second order aisle term and interaction term included.
Figure 76. Summary of residuals for Barn 3 path loss model after including an interaction term for log of separation distance and aisle separation distance.

A scatter plot of the input RSSI values versus the model fits further emphasizes the high correlation of the model (Figure 77). The slope of the regression was uniquely equal to one and there was no sign of non-linearity.
Figure 77. Scatterplot of predicted versus true RSSI values based on the Barn 3 model including a second order aisle term and an interaction term.

5.4.3. Verification of 2D Signal Attenuation Model by Comparison to 2nd Test Building

A full sight survey was also performed on a second CAFO facility which was identical to the barn used to create the response model (Figure 78). Attenuation data for separation distance and cage separation were used to evaluate the accuracy of the model and analyze its ability to predict performance for a building with no prior test data. The experimental data was compared to the model data and a full set of error values were established across both transmission distance and cage separation. One statistical outlier was removed which was most likely caused due to
fast fading during data collection. The 95% confidence interval for model error produced a range of (-1.25, -0.14) dB with a mean error of -0.7 dB (Figure 79). This indicated that the signal attenuation within the second test facility was on average 0.7 dB greater than the model predicted.

Figure 78. Barn 4 actual path loss response when measured with a stationary transmitter located in the center of the building and a movable receiver used to measure path loss in units of RSSI.
Figure 79. Statistical summary of error in estimation of Barn 4 RSSI values from a predictor model developed based on a Barn 3 dataset.

A full matrix plot was created to compare the response of the model to the true attenuation of both test barns, the residuals of the second barn, and all input factors (Figure 80).
Figure 80. Matrix plot of input variables and residual values for comparison of Barn 3 model predictions, Barn 4 true values, and residuals.

The matrix plot of response and predictor variables highlights several key areas of interest. First, the error in predicting the response of the second facility was not randomly distributed versus the aisle separation or the distance. This result was indicative of the reduced accuracy in the prediction model at the extremes of the model where the asymptotic response exists. The prediction model also tends to underestimate path loss at lower true RSSI values and overestimate path loss at higher RSSI values.

Errors associated with the prediction model tended to oscillate between positive and negative values (Figure 81). This response was due to differences
between the smoothed predictive model and the variable true response which included additional uncertainty caused by fast fading.

Figure 81. Contour plot of error between Barn 4 actual path loss and predicted path loss based on the final predictor model.

Overall though, the predictive model adequately predicted the path loss of a two dimensional poultry layer facility with a mean level of error less than 1.25 dB. This error was well within acceptable limits and has verified that the model can be used for optimization of wireless node placement within a CAFO. The contour plot does show areas where the path loss estimate varied significantly from the true path loss (Figure 81). Most notably, the model smoothes the expected response and has no means to predict fast fading conditions. This can be directly seen by the variation
in prediction error along the zero aisle separation condition. Also, the model has a tendency to underestimate path loss when the separation distance was near zero. Under this condition, the model could be improved by including a qualitative path loss parameter that would activate only under conditions where the linear separation distance was less than 10 feet. After this point, the two dimensional model was much more accurate in its predictions.

For wireless networks to accurately communicate between individual points, a sufficient combination of signal strength, antenna gain, and path loss must exist. This model allows one parameter, the path loss, to be accurately known between two potential sensor locations. With this value known, the transmission power and antenna gains can be sized appropriately to maintain the overall system power above the receiver sensitivity level. This will guarantee a reliable data link while minimizing the overall power consumption and minimizing antenna gain. All high gain antennas exhibit some level of directionality, so by minimizing the antenna gain the design also incorporates the highest level of isotropic characteristics.

For multi-hop and networks to expand over the entirety of a CAFO facility, a critical path between a backbone of nodes must exist to allow communication throughout the facility. Once established, individual nodes may be placed at any location within communication range of at least a single main node. The overall reliability of the network will be governed by the individual nodes ability to route messages back to a single network sink or data logger. The low temporal variability in path loss will help encourage mesh networking within CAFOs, but individual designs will still need to specify the maximum path loss acceptable between nodes.
The absolute maximum value can be established based on the antenna gain, transmission power, and receiver sensitivity characteristics of individual nodes. A factor of safety should be added though to account for changes in antenna efficiency caused by dust buildup on the enclosure surface or other sources of yet unknown path loss. Critical path nodes which makeup the backbone of the mesh network will require a constant power supply so that they can serve the remote end nodes as a message router. The end nodes can operate in a reduced power state until a specific time when a measurement point will be recorded and transmitted to the network sink.

5.4.4. **Limitations of Two Dimensional Path Loss Model**

Although the two dimensional model results provided and excellent means to predict path loss within a CAFO poultry layer facility and was verified through a comparison with another representative site, several application limitations do exist for extended use of this model. First, this model was created under the maximum operating conditions of 170 ft transmission distances and 3 aisles of cage separation. Serious prediction errors can occur if the model is applied outside of these bounds. Arguments could be made that the transmission distance could be extended based on the fundamental understanding of path loss in free space, but the same cannot be said with regards to the cage separation terms. Specifically, the second order cage separation term cannot under any circumstance be used outside the maximum bounds of 3 cages. If applied outside these limits, the second order term will increase dramatically and cause an overall reduction in path loss as the number of
cages increase. This of course is not realistically possible and was simply a sign of the firm application limits of this work. Furthermore, this work was based on data collected from 2.4 GHz radio transceivers and should only be used to design other systems utilizing the same frequency band. Nearly isotropic antennas were used in this development and the model provides no means to respond to changes in antenna characteristics such as increased gains through directional focusing of the antenna output.

5.4.5. SYSTEM REQUIREMENTS FOR SUCCESSFUL WIRELESS CAFO COVERAGE

The results of the path loss models can be used to better understand the wireless systems requirements for a successful wireless sensor network deployment. The key to successful networking is maintaining a positive link budget, which indicates that the power available at the receiver is greater than its internal sensitivity. The application goal is to cover the largest area possible within a CAFO with wireless sensors, thus the critical transmission distances and cage separations must be identified.

Based on a link budget analysis, the governing equation for a successful wireless link was (Equation 37):

\[ \text{Link Budget} = P_r - PL + P_t \]

Equation 37. Wireless path loss link budget equation (Balanis, 2005).
Where:

\[ P_r = \text{Receiver Sensitivity (dB)} \]
\[ PL = \text{System Path Loss (dB)} \]
\[ P_t = \text{Power Transmitted (dB)} \]

Again, if the link budget is a positive number then a successful wireless link will be formed. The previously described factor specific path loss model can serve as a direct estimate for the system path loss (PL). The receiver sensitivity and transmission power are solely based on the specifications of the hardware. These parameters should be considered during the network design phase because excess transmission power will increase the overall power consumption of the system and thus reduce battery life. Furthermore, the positive magnitude of the link budget serves as a factor of safety for the wireless design. The level of fast fading in the environment should be carefully considered and the required link budget adjusted appropriately to insure a factor of safety greater than the fast fading variance in signal strength.

For the buildings studied during this work, the overall length was 400 ft (122 m). In order to calculate the power requirements to link wireless nodes across the entire length of the facility in a point-to-point system, the linear distance path loss model is used:

\[ PL = -27.83 - 25.86 \log(\text{Distance}) = -27.83 - 25.86 \log(400) = -95 \text{ dB} \]

When incorporated into the link budget equation for a 400 ft single link transmission we find:

\[ \text{Link Budget} = P_r - 95 \text{ dB} + P_t \]
In this case, the sum of the receiver sensitivity and the transmission power must be greater than 95 dB plus any desired factor of safety associated with fast fading. We are then left with a single equation and two unknown factors. In order to solve this design criteria one of the unknown factors must be chosen or a pair of nodes can be evaluated based on a trial and error method. Since the transmission power is directly related to the power consumption of the node, it is often desirable to minimize this to a unit gain or 0 dB. In this case the minimum receiver sensitivity is required to be 95 dB, but again no factor of safety is included. Data for temporal distribution testing has shown that fast fading is a major concern in CAFO facility and as such a factor of safety of nearly 10 dB should be included to ensure successful data transmission. This results in an overall receiver sensitivity requirement of 105 dB.

Receiver sensitivity is a set parameter based on the specifications of the hardware used in a design. Typically, price is proportional to receiver sensitivity and a specified sensitivity may not be achievable given the budget or other limits of a project. In this case, the transmission power must be amplified. If the 400 ft transmission distance is again considered with a limitation of a maximum receiver sensitivity of 90 dB, then the transmitter would be required to provide a 15 dB gain. This relates to a transmission power of 31.6 mW, which will also increase the system power consumption when compared to a unity gain design.

The same design concepts can be used to calculate required receiver sensitivity and transmission power based on any path loss characteristic. When experimental data is note available to help predict path loss, greater factor of safety
levels should be adopted. Also, the context of the path loss models in this work should be considered when applying it to other CAFO systems. These models should never be used outside of the level of scale used in their development, especially when higher order terms are included in the original model.

5.5. CONCLUSIONS

The results of this work provide the first documentation of path loss and wireless signal attenuation within large scale poultry layer facilities. The application of this work will lead to the development and deployment of advanced sensor networks to improve the quality, density, distribution, and flexibility of data acquisition systems in this environment. These advanced networks will then enable widespread monitoring on a scale currently not feasible and will enhance researchers’ ability to understand and model the dynamic building environment.

It was found that many building related parameters, such as transmission distance, cage separation, concrete separation, antenna orientation, node height, and animal presence all exhibited significant levels of attenuation impact. It was also shown that for most general scenarios, a two-dimensional model could be applied to predict path loss within a building environment with only two factors, transmission distance and cage separation. For improved accuracy, the predictive model included first order terms for transmission distance and cage separation as well as a second order term for cage separation and an interaction term for both first order variables. The final model provided an $R^2$ value of 86.7%, which indicated that only 13.3% of system variations were not accurately described by the predictive model. This model, based on experimental RSSI measurements and verified through testing in a
second representative facility, was found to accurately predict path loss and provided mean path loss estimation errors of nearly zero.

Finally, as the system requirements revealed, it is a great challenge to cover the extent of a CAFO facility with a point-to-point wireless sensor network. As the wireless link budget revealed, the high levels of path loss exhibited in these environments would cause each individual sensor to maintain a high level of receiver sensitivity as well as transmission power. This would increase both the cost and power consumption of the network, thus decreasing the usability and flexibility which were such key focus areas for the future use of this work. An alternative solution is to reduce the individual node requirements and use a method of enhanced networking to allow localized nodes to communicate directly and access larger network areas by routing messages through multiple localized sensors. This technology, introduced earlier as mesh networking, could provide the linkage to extend this new knowledge of the transmission requirements within a CAFO and develop a workable sensor network system for enhanced, distributed environmental monitoring.
CHAPTER 6

DEVELOPMENT AND EVALUATION OF A MULTI-POINT WIRELESS SENSOR NETWORK FOR POULTRY FACILITIES

6.1. INTRODUCTION

The previous chapter has provided models and experimental data to fully understand many of the characteristics which impact path loss within CAFO environments. These losses will limit the communication reliability between neighboring nodes and will limit the overall data transmission coverage with a full scale facility. It was suggested though that an alternative solution to wide scale deployment and coverage of wireless sensors would be to use mesh networking, in which each individual node makes up a small part of the entire network backbone, as a solution to limited transmission distances. If successful and reliable, the backbone network will provide ubiquitous network access from any location within the CAFO. Researchers can then add or relocate individual sensors nodes freely, without limitation related to wire length or channel capacity of wired data acquisition systems.
When designing the layout for a wireless mesh network, considerations should be made to the required sensor density to maintain communication, and redundant communication when possible, across the entirety of the physical environment being monitored. For this to occur, information must be available regarding the expected path loss in this specific environment. Also, the rate and synchronization method of the network should be specified. If significant numbers of sensor nodes are required to stay at full power all the time, it may be suggested to supply these nodes with direct power rather than from a battery supply.

6.2. OBJECTIVES

The core objectives of this chapter were to fully characterize a mesh network design that would be suitable for use in a CAFO environment and to verify this design through a series of field tests conducted in a poultry layer facility. The main parameter of interest in the evaluation of mesh networks was message error rate (MER), which provides a direct measurement of network reliability. Specifically the following objectives were addressed:

a. Develop a wireless network for use in a CAFO environment,

b. Describe the power consumption characteristics of mesh network nodes and project potential battery life for a common CAFO sensing application,

c. Verify the reliability of an active mesh network through the collection of MER data within a poultry layer facility, and

d. Conduct a case study of a wireless mesh networking temperature sensor and data logging system for CAFO environmental monitoring.
6.3. METHODS

6.3.1. Selection of Wireless Network Protocol

Mesh networking was chosen as the desired protocol for this study based on its ability to interlink multiple sensors over the same backbone and allow for automatic routing of messages through neighboring nodes. Many commercial products exist which can implement some form of mesh networking, but each have individual selection criteria to customize a user's approach to mesh networking. Operating frequencies of 900 MHz and 2.4 GHz were available. It was well known that lower operating frequencies will exhibit lower path loss levels, but that higher operating frequencies offer additional bandwidth and data transfer capacity. The majority of commercial sensor systems are moving towards 2.4 GHz applications and as such it was decided that this project would also use the 2.4 GHz operating frequency. The additional bandwidth was not necessary, because of the traditionally low sampling rates required for CAFO monitoring, but in order to service the larger goal of this work and to provide information that will have a lasting impact on future designs of wireless systems in agricultural system monitoring, 2.4 GHz was the optimal choice.

Many options also exist for selection of receiver sensitivity and antenna gain. It was determined that for the widespread use of wireless networking, it would be ideal to minimize the overall cost of each node. To achieve this criterion, a standard receiver sensitivity within the 85 – 95 dB range would be chosen. Also, high gain antennas, which were commercially available, were not used in this study because of
their increased cost, increased installation footprint, and tendency to become non-isotropic. Finally, as a means to maintain these results in a form that could be widely applied outside of this publication, a 1 mW transmitter power would be used. This transmission power rating allows future designers to have a direct benchmark of system performance versus a unit gain transmitter.

It was not a specific requirement of this work that the nodes be linked through a standardized network protocol, just that they link through a mesh network. As a design decision though, the Zigbee mesh networking protocol was chosen for this project because of its recent popularity with network designers and its growing commercial availability. Although these evaluation steps aim to measure the reliability of mesh networking, by extension, they will also serve as an initial study of the reliability of Zigbee nodes.

6.3.2. Selection of Test Device

The ETRX1 Zigbee transmitter (Telegesis Inc.) was again chosen as the test node for evaluating full scale implementation and reliability of mesh networks. There were several key characteristics to this Zigbee module which made it an advantageous choice for this work including:

a. Automatic Zigbee network configuration,

b. Dual, 12-bit analog input ports and eight digital input/output ports,

c. Software programmable network settings including:
   a. PAN number,
   b. Channel ID,
c. Node ID,
d. Sleep timers,
e. Automated data sampling and reporting, and
f. Automated sink configuration.
d. Low power consumption (30 mAmp TX, 30 μA sleep),
e. Ideal receiver sensitivity (90 dB),
f. Programmable transmit power, and
   a. Including 1 mW (0 dB) rate used during this study,
g. Serial access to individual RSSI.

6.3.3. Prediction of Wireless Transmission Performance

Based on the results from Chapter 4, it was known that path loss attenuation would be much more significant when transmitting data through cages rather than within the same aisle way. To maximize the reliability of the network under these conditions, it was critical that backbone nodes be distributed in a grid pattern to minimize transmission length while crossing over cages and then maximize overall coverage area by transmitting much longer distances within the same aisle way. The maximum aisle separation distance and the maximum cage separation value can be calculated based on the path loss predictor model previously developed. Again, the successful network deployment will require a positive link budget and will require a factor of safety to overcome localized fast fading effects. Specifically in this case, the link budget equation becomes:
Link Budget = \( P_r - PL + P_t - FS \)

**Equation 38.** Modified link budget equation to include factor of safety for reliable wireless data transmission (Derived by Author).

Where:

- \( P_r \) = Receiver Sensitivity (dB)
- \( PL \) = System Path Loss (dB)
- \( P_t \) = Power Transmitted (dB)
- \( FS \) = Factor of Safety (dB)

The receiver sensitivity was defined by the choice of the ETRX1 module and will maintain constant at 90 dB. The transmission power was also known to be programmable and a 1 mW (0 dB) power was chosen for all studies. The factor of safety was set to 8 dB based on results from a temporal analysis of path loss in CAFOs. This results in a critical system path loss of 82 dB.

When considering transmission distance within a single aisle only, the path loss was governed by (Equation 39):

\[ PL = -27.83 - 25.86 \log(\text{Distance}) \]

**Equation 39.** Path loss model within single aisle way of poultry layer facility (Calculated by Author).

When set to -82 dB, this represents the largest distance which individual Zigbee nodes can be spread within a single aisle and still maintain a reliable level of communication. The solution to this formula was a critical separation level of 125 feet.
For aisle separation, the link budget model will maintain the same form, but the factor of safety was increased to 10 dB, due to results showing higher levels of signal variability when transmitting through cage obstructions. It was also noted that it would be very difficult to place individual nodes directly in line with one another, because there was no line of sight path to visual inspect each installation location. This was overcome by using an offset of 5 feet and the two-dimensional path loss model to predict the critical cage separation value (Equation 40).

\[
PL = -32.9 - 28.5 \times \text{Aisle} + 4.19 \times \text{Aisle}^2 - 23.7 \log(D_{nt}) + 6.58 \text{Aisle} \times \log(D_{nt})
\]

Equation 40. Two dimensional path loss model for poultry layer facility (Calculated by Author).

With the linear separation distance set to 5 feet and the overall path loss set to 80 dB, it was found that the critical cage separation value was 2 cages. These two parameters, 125 feet and 2 cages separations, define the pattern of node distribution within a poultry layer facility CAFO and will be used as the basis for reliability testing.

6.3.4. **Experimental Design**

To evaluate the reliability of the Zigbee mesh networking nodes, a sample network will be installed with nodes distributed over a grid pattern within a poultry layer facility. Trial 1 will be conducted within a single barn and will be wirelessly connected to the network sink which will be located external to the barn (Figure

230
Nodes will be separated by 125 feet and 2 cages initially. Trial 2 will use additional separation distance values to determine the accuracy of the link budget model as well as the estimation for the required factor of safety (Figure 85). Trial 3 will be conducted with mesh nodes located in two separate buildings and link wireless through an external sink node (Figure 88). Sensors will be located on multiple building levels and will be required to verify real-time access to all data points.

Reliability was evaluated based on the message error rate of the sensor network. Each node was programmed to transmit a message, which included its current values for both analog inputs and all eight digital inputs, to the network sink at a precise 5 second timing interval. Messages recorded by the sink were transmitted serially to a computer which ran a dedicated data logger program. The software application decoded the messages upon receipt to determine the sensor node which initiated the transfer and time stamped the message before exporting it to a data file. Post processing of the data was performed to analyze the time difference between subsequent messages from an individual node. Based on the known network run time, the theoretical number of received messages could be easily calculated. The MER value was directly calculated by dividing the difference between true and theoretical message reception count by the theoretical message reception count. Results were reported as both MER and total number of message counts. A minimum of two hours of continuous sensor data was required to yield MER results.
6.4. RESULTS AND DISCUSSION

6.4.1. Power Consumption Characteristics of Zigbee Nodes

The power consumption of a Zigbee node was dependent on many factors including, network structure, node routing responsibilities, transmission power, standby power efficiency, and auxiliary node components. A full featured Zigbee node was required to maintain full power at all times to allow for routing responsibilities throughout a mesh network. This functionality virtually requires that the node be powered by a constant supply rather than a battery. Common Zigbee nodes, such as the Telegesis ZIGBEE used in this study, consume between 26 to 30 mAmps continuously when in full power mode. A common high capacity 2400 mAh battery would only supply enough energy for 2.5 days of operation. End Device nodes or nodes which have no routing responsibilities can achieve much higher battery efficiency by turning the radio and microcontroller off during non-transmission times.

A typical configuration would allow an End Device to wake from a low power sleep mode, acquire data from analog channels, transmit the data to the network datalogger, listen for a confirmation reply, then return to sleep mode. In order to test the power consumption of the ZIGBEE wireless node a sink and data transmitter were joined into a wireless PAN. The sensor node was powered from a steady 3.0 volt supply. The positive leg of the power supply was modified to contain a precisely measured 9.8 ohm resistor in series. By monitoring the voltage drop across this inline resistor, the current consumption of the device was determined. The
transmitter was configured to enter a deep sleep mode between transmissions. The
sleep delay was tested at both 5 seconds and 1 minute.

Because the voltage of interest was extremely low, the data logging system
was calibrated before and after the test procedures. A USB-1608, 16-bit data logger
from Measurement Computing Corporation was used to monitor the voltage drop at
a rate of 667 Hz. This was the fastest sampling speed that could successfully receive
a new voltage reading through the USB port then scale and store the returned value.
An expected transmission current of 25 mAmps would result in a voltage drop of
0.245 volts, thus the range of the USB-1608 was set to ±1 V. This provided a
measurement resolution of 30.5 µVolts which related to a current resolution of 3.11
µAmps. A zero calibration was conducted by connecting the analog input on channel
zero to the shared analog ground channel. The results revealed a zero bias of 0.0016
volts. This zero calibration was repeated at the end of the testing period and the
same 0.0016 volt bias was present. To account for this bias, all analog reading were
scaled down by a uniform 0.0016 volts.

Results of the 5 second transmission interval test revealed a very repeatable
pattern of high current consumption periods during transmission events and low
current consumption during standby events (Figure 82). Each transmission event
peaked at nearly 29 mAmps.
A closer inspection of one unique transmission event shows variations in current consumption during the course of the event (Figure 83). After a short startup period, the node very quickly reached its maximum 29 mAmp current consumption during the transmission of its sensor data. It then waited for a longer period before the message was acknowledged by the receiver. The length of the waiting period was heavily dependent on the network topology, as multiple hop messages take significantly longer to be acknowledged than the single hop message presented.
Further analysis of the data yields an average transmission power of 27.5 mAmps with a maximum single hop transmission time of 0.1 seconds. The standby power was calculated to be 0.03 mAmps and the duration of the standby time was determined by the desired sampling period. A table of weighted current consumption data based on sampling interval shows the increasingly reduced current consumption the sampling interval increases (Table 11).
Table 11. Cumulative current consumption of wireless sensor module based on ratio of sleep and transmission times.

These results can also be applied to battery life of a specific sensor node. Based on standard 3 V battery configurations of 240, 600, 900, 1200, 1500, and 2400 mAmp-hr, the maximum operating period for the wireless node was calculated (Table 12). A standard 1200 mA-hr battery which reports sensor data on 1 minute intervals could sustain a useful life of 659.8 days.

<table>
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<th>Sampling Interval (sec)</th>
<th>Standby Current (mA)</th>
<th>Transmit Current (mA)</th>
<th>Transmit Time (sec)</th>
<th>Weighted Current (mA)</th>
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</thead>
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<td>27.5</td>
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</tr>
</tbody>
</table>

Table 12. Expected sensor battery life based on various commercial battery power capacities.

<table>
<thead>
<tr>
<th>Sensor Life for Various Battery Supplies (days)</th>
</tr>
</thead>
<tbody>
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<td>Battery Power Capacity (mA-hr)</td>
</tr>
<tr>
<td>Sampling Interval (sec) 240 600 900 1200 1500 2100 2500</td>
</tr>
<tr>
<td>5</td>
</tr>
<tr>
<td>30</td>
</tr>
<tr>
<td>60</td>
</tr>
<tr>
<td>180</td>
</tr>
<tr>
<td>300</td>
</tr>
</tbody>
</table>

6.4.2. **Reliability Testing of a Zigbee Mesh Network**

Models for wireless performance have been developed to predict limitations and spacing intervals for wireless sensors in CAFOs. These models were verified
through empirical measurement of RSSI values at specific sensor intervals. An additional verification process involves creating a wireless mesh network covering a wide area within a CAFO and evaluating performance based on the message error rate (MER). The MER is the critical factor which indicates whether the sensor messages were actually received at the desired location. A series of MER trials were conducted to evaluate the effectiveness of mesh networks for CAFO monitoring under various performance criteria.

The network topology used consisted of a thirteen node mesh network employing the wireless sensor nodes described previously. Twelve nodes were interfaced with thermistors to allow for temperature measurement. Each of these nodes was programmed to report the temperature data to a specific sink node at a rate of 0.2 Hz. The sink node then forwarded the sensor data to a computer via an RS232 serial port. A customized data acquisition software was developed in Visual Basic to read the inbound data and store the sensor information along with a time stamp of arrival. The MER was calculated by dividing the actual number of valid sensor data points by the theoretical number of temperature data points over the collection interval. Additional statistics used to describe the performance of the system included the average time between received messages. During all studies, all wireless nodes shared the same Zigbee PAN, operating frequency, and transmission channel.
**Trial 1: Verification of Predicted Mesh Network Results**

Trial 1 was conducted with all sensor nodes in Barn 3. Eleven nodes were spread throughout the entirety of Barn 3 and one additional node was placed on the external walkway to the barn. Each node within a unique aisle was separated by a linear distance of 125 feet and 2 aisle way separations (Figure 84). These treatment factors were chosen based on performance predictions from Chapter 4 modeling results. Sensor location ID 13 was setup as the network sink and allowed for direct access from an external computer to all nodes within the network. Data was logged continuously for a seven and one half hour interval. Results of the MER analysis again showed excellent reliability from the sensor nodes (Table 13). One single node at location 3 did experience an extended period of inactivity which resulted in it being dropped from the network. After it was able to reconnect with its nearest neighbor it was able to maintain communication through the duration of the study.
Figure 84. Topology of wireless nodes in Trial 1. Node 13 was programmed as the network sink.
<table>
<thead>
<tr>
<th>Location ID</th>
<th>Total Counts</th>
<th>MER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5383</td>
<td>0.11%</td>
</tr>
<tr>
<td>2</td>
<td>5353</td>
<td>0.67%</td>
</tr>
<tr>
<td>3</td>
<td>5163</td>
<td>4.19%</td>
</tr>
<tr>
<td>5</td>
<td>5384</td>
<td>0.09%</td>
</tr>
<tr>
<td>6</td>
<td>5394</td>
<td>-0.09%</td>
</tr>
<tr>
<td>7</td>
<td>5385</td>
<td>0.07%</td>
</tr>
<tr>
<td>8</td>
<td>5366</td>
<td>0.43%</td>
</tr>
<tr>
<td>9</td>
<td>5385</td>
<td>0.07%</td>
</tr>
<tr>
<td>10</td>
<td>5368</td>
<td>0.39%</td>
</tr>
<tr>
<td>11</td>
<td>5369</td>
<td>0.37%</td>
</tr>
<tr>
<td>12</td>
<td>5385</td>
<td>0.07%</td>
</tr>
</tbody>
</table>

Table 13. MER values for Trial 1 with linear separation distances of 125 feet and 2 aisle way separations.

The result of the MER study verified the estimation of network limitations as designed by the application of previously discussed path loss models. Further validation was conducted to understand the accuracy of the factor of safety choice by repeating an identical study under the transmission distance conditions of 150 feet.

**TRIAL 2: VERIFICATION OF FACTOR OF SAFETY**

Trial 2 was conducted with all sensor nodes in Barn 3. Eleven nodes were spread throughout the entirety of Barn 3 and one additional node was placed on the external walkway to the barn. Each node within a unique aisle was separated by a linear distance of 150 feet (Figure 85). Data was logged continuously for a one hour interval. Results of the MER analysis again showed excellent reliability from the sensor nodes (Table 14).
<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Location ID</th>
<th>Counts</th>
<th>MER</th>
</tr>
</thead>
<tbody>
<tr>
<td>3CCC</td>
<td>1</td>
<td>619</td>
<td>-0.26%</td>
</tr>
<tr>
<td>3C9C</td>
<td>2</td>
<td>617</td>
<td>0.06%</td>
</tr>
<tr>
<td>3CCD</td>
<td>3</td>
<td>616</td>
<td>0.23%</td>
</tr>
<tr>
<td>3C3D</td>
<td>4</td>
<td>619</td>
<td>-0.26%</td>
</tr>
<tr>
<td>3C9E</td>
<td>5</td>
<td>617</td>
<td>0.06%</td>
</tr>
<tr>
<td>3C7D</td>
<td>6</td>
<td>617</td>
<td>0.06%</td>
</tr>
<tr>
<td>3CA6</td>
<td>7</td>
<td>614</td>
<td>0.55%</td>
</tr>
<tr>
<td>3D75</td>
<td>8</td>
<td>616</td>
<td>0.23%</td>
</tr>
<tr>
<td>3C7C</td>
<td>9</td>
<td>614</td>
<td>0.55%</td>
</tr>
<tr>
<td>3CB9</td>
<td>10</td>
<td>613</td>
<td>0.71%</td>
</tr>
<tr>
<td>3CAF</td>
<td>11</td>
<td>614</td>
<td>0.55%</td>
</tr>
<tr>
<td>3DA1</td>
<td>12</td>
<td>616</td>
<td>0.23%</td>
</tr>
</tbody>
</table>

Table 14. MER values for wireless nodes in Trial 2.
Figure 85. Topology of wireless nodes in Trial 2. Node 13 was programmed as the network sink.
Figure 86. Interval plot showing the bounds of the ANOVA results for a 95% confidence interval of the mean for wireless signal reception under Trial 2 conditions. Label format is Node ID – Location Number.

The ANOVA results again show strong correlations between the programmed transmission interval of 5 seconds and the calculated transmission interval as recorded by the network data logger (Figure 86).

A longer duration study was conducted to determine if the quality of signal changed significantly over time, leading to increased occasions of sensor failure. Location ID 6 was removed during this study to increase the probability of message failure. Results did reveal an increase in the MER especially for nodes located near the end of the building farthest removed from the data logger. These nodes were required to transmit data through the greatest number of mesh hops and thus had
the highest probability of message failure. Again, all nodes located within the same aisle where separated by 150 feet.

<table>
<thead>
<tr>
<th>Location</th>
<th>Counts</th>
<th>MER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2392</td>
<td>13.60%</td>
</tr>
<tr>
<td>2</td>
<td>2612</td>
<td>5.66%</td>
</tr>
<tr>
<td>3</td>
<td>2553</td>
<td>7.79%</td>
</tr>
<tr>
<td>4</td>
<td>2538</td>
<td>8.33%</td>
</tr>
<tr>
<td>5</td>
<td>2749</td>
<td>0.71%</td>
</tr>
<tr>
<td>6</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>2758</td>
<td>0.38%</td>
</tr>
<tr>
<td>8</td>
<td>2754</td>
<td>0.53%</td>
</tr>
<tr>
<td>9</td>
<td>2740</td>
<td>1.03%</td>
</tr>
<tr>
<td>10</td>
<td>2748</td>
<td>0.74%</td>
</tr>
<tr>
<td>11</td>
<td>2769</td>
<td>-0.01%</td>
</tr>
<tr>
<td>12</td>
<td>2725</td>
<td>1.57%</td>
</tr>
</tbody>
</table>

Table 15. Summary of Message Error Rates for 12 nodes in extended duration study defined as Trial 2 with node 6 intentionally removed to increase the likelihood of message error.

A closer inspection of the MER results show an inflation caused by specific events of lost signal. Over the course of the 3.8 hour sampling time, only 60 transmission events were delayed due to poor network connectivity. Furthermore, of these events, only 9 transmissions were delayed more than 1 minute with a maximum message delay time of 5.7 minutes. Under all circumstances of lost communication, the transmitting node was able to rejoin the mesh network through a different architecture. When comparing the MER values for 125 ft and 150 separation distances, it was clear that the 125 ft separation distance provided an increased level of reliability and as such the 10 dB factor of safety used in the design of the optimal network topology should be maintain in future designs.
Figure 87. Comparison of MER values for similar node topologies with 125 and 150 foot separation distances.

**TRIAL 3: MULTI-BUILDING NETWORKING VERIFICATION**

A final trial was conducted to evaluate the ability of multiple sensors to be linked across multiple buildings. Because of the high attenuation rates caused by steel siding and other structural materials, an intermediate node was placed between the two test buildings in order to allow a full network bridge. Trial 3 was conducted with 7 sensors in Barn 3, 3 sensors in Barn 4, and 2 sensors linking Barn 3 and Barn 4. In Barn 3 all sensors were on the upper level, while in Barn 4 sensors were located on the upper and lower level (Figure 88). Nodes located within the same aisle were separated by a linear distance of 125 feet. Data from one sensor in
Barn 3 (location ID 6) was invalidated due to a faulty battery connection that prevented it from sending or receiving data. The MER values for all remaining sensors are shown below (Table 16):

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Location ID</th>
<th>Building Level</th>
<th>Counts</th>
<th>MER</th>
</tr>
</thead>
<tbody>
<tr>
<td>3C9E</td>
<td>1</td>
<td>Upper</td>
<td>1688</td>
<td>3.29%</td>
</tr>
<tr>
<td>3CB9</td>
<td>2</td>
<td>Upper</td>
<td>1745</td>
<td>0.02%</td>
</tr>
<tr>
<td>3D75</td>
<td>3</td>
<td>Upper</td>
<td>1743</td>
<td>0.14%</td>
</tr>
<tr>
<td>3C3D</td>
<td>4</td>
<td>Upper</td>
<td>1748</td>
<td>-0.15%</td>
</tr>
<tr>
<td>3C7C</td>
<td>5</td>
<td>Upper</td>
<td>1746</td>
<td>-0.03%</td>
</tr>
<tr>
<td>3DA1</td>
<td>6</td>
<td>Upper</td>
<td>0</td>
<td>100.00%</td>
</tr>
<tr>
<td>3CA6</td>
<td>7</td>
<td>Upper</td>
<td>1745</td>
<td>0.02%</td>
</tr>
<tr>
<td>3CAF</td>
<td>8</td>
<td>Upper</td>
<td>1745</td>
<td>0.02%</td>
</tr>
<tr>
<td>3CCD</td>
<td>9</td>
<td>Upper</td>
<td>1745</td>
<td>0.02%</td>
</tr>
<tr>
<td>3C9C</td>
<td>10</td>
<td>Lower</td>
<td>1746</td>
<td>-0.03%</td>
</tr>
<tr>
<td>3C7D</td>
<td>11</td>
<td>Upper</td>
<td>1744</td>
<td>0.08%</td>
</tr>
<tr>
<td>3CCC</td>
<td>12</td>
<td>Upper</td>
<td>1745</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

Table 16. Message error rate values for wireless nodes under configuration described by Trial 3.
These MER results demonstrate excellent sensor reliability (Figure 89). The second measurable parameter was the randomness of the reception interval. It was highly desirable that repeated measurements arrive very near the five second interval programmed into the sensors. An individual value plot was used to evaluate the spread in sensor response time delay. Node 3C9E (location ID 1), which reported the highest MER in the previous analysis shows several data points in which an unacceptable time delay exists. The maximum time delay was 140 seconds.
in which no data was received from the sensor. It is noted that the location of this node is on the outer edge of the sensor network and only location ID 3 is within range of location ID 1. This eliminated the robustness of the mesh sensor network by not allowing location 1 to choose a secondary transmission route if the connection to location 3 is broken.

![Figure 89. Individual value plot of delay time for each wireless node in Trial 3. Label format is Node ID – Location Number.](image)

An Anova was also conducted on the response data which shows the ten of eleven sensors having a close association to the five second sampling interval (Figure 90). It was noted that the standard deviation of the sampling interval was
artificially skewed based on the one second sampling resolution of the data logging computer.

![Interval plot showing the bounds of the ANOVA results for a 95% confidence interval of the mean for wireless signal reception under Trial 3 conditions.](image)

Results indicated that it was achievable to span multiple buildings with the Zigbee mesh networking. Path loss characteristics were found to be very near predicted values and a factor of safety of 10 dB improved the overall network reliability. With this stated factor of safety, the link budget equation, along with path loss predictions from models described in Chapter 4, can provide accurate estimates as to the optimal design and layout of full scale wireless mesh networking systems.
6.4.3. **Case Study of Wireless Network Design**

As discussed previously, power consumption varies dramatically between active transmission and passive sleep modes of wireless transmitters. The ZIGBEE module maintains a power consumption range of 29 mAmps during transmission and 0.03 mAmps during sleep. Based on this information, the total power consumption required by a wireless node is calculated by (Equation 41):

\[
\text{Power Required (mA - hr)} = \frac{i_t t_t + i_s t_s}{t_{total}} x t_{life}
\]

Equation 41. Calculation of wireless sensor power requirements when used in sleep mode (Derived by Author).

Where:
- \( i_t \) = current during transmission (mAmps)
- \( t_t \) = time during transmission (sec)
- \( i_s \) = current during sleep (mAmps)
- \( t_s \) = time during sleep (sec)
- \( t_{total} \) = time between transmissions (sec)
- \( t_{life} \) = expected life of sensor (hrs)

Wireless transmitters themselves typically maintain excellent sleep characteristics in order to minimize the overall power requirements of a node, but the total system power will be impacted by other hardware components as well. Specifically any peripheral circuits either for voltage regulation, sensor conditioning, data storage, or display indicators will draw additional power which will limit the
overall life of the sensor. When designing wireless sensor nodes these factors should be taken into account in all phases of design to prevent premature node failure due to a single high load device.

The voltage regulation circuit is critical to provide a precise voltage reference to the sensors and embedded controllers. Unfortunately, linear voltage regulator circuits inherently have high levels of quiescent current and cause high load for battery circuits. Depending on the application though, it is possible to design a wireless node without any voltage regulation. The key to determining whether a voltage regulator is required is to consider the type of analog to digital converter used in a microcontroller circuit. If the reference voltage of the microcontroller is tied directly to the input voltage and does not require a specific voltage level, then the output digital value will also be in reference to a floating battery level. This can lead to a robust design if the sensor that’s being implemented also has an output which floats relative to the input voltage.

In the case of the ZIGBEE module, the analog to digital converter uses an internally powered 1.2 volt supply as the reference voltage for the analog to digital converter. This module also has a separate 1.8 volt regulator that only turns on during the active mode and that is used to power the module’s microcontroller. If we consider interfacing this module directly with a resistive based temperature sensor like a thermistor, it is noted that the thermistor bridge supply must be driven by one of the regulated sources rather than directly by the changing battery source. The thermistor bridge will add to the overall power consumption of the circuit and should be carefully designed to limit the overall power consumption.
Considering an example design in which the ZIGBEE module will be interfaced with a thermistor temperature sensor and designed to operate from a single battery source for a 5 year life. The thermistor bridge would be directly connected to a digital output pin of the ZIGBEE which is programmed to output a high logic during the active state of the node. This high voltage signal, which should be equivalent to the 1.8 volt internal reference will be sufficient to power the thermistor bridge. In order to minimize power consumption, a B57891 100kOhm thermistor will be used in series with a static bridge resistor. This particular thermistor supplies resistance tolerances of ±1%. When connected on the lower end of a 200 kOhm static resistor, the bridge circuit will output a voltage change from 0.918 – 0.428 for a temperature change from 10 – 35°C. Based on the 16 bit ADC resolutions of the ZIGBEE module, this voltage span will relate to a temperature resolution of 0.001°C/bit. The accuracy of the system will be determined by the ±1% accuracy of both the thermistor and the resistor. During the maximum condition when the two elements drift in opposite directions the voltage difference between the ideal case and the skewed case will reach 7.97 mVolts. This will yield a drift error of 0.4°C. The minimum additive power consumption will occur during the lowest resistance level and will be no greater than 6.9 μAmps. This level of current consumption will be insignificant to node operation.

6.5. CONCLUSIONS

The conclusion of this chapter results in a clear picture of the reliability and design of multi-sensor wireless mesh networking technology for CAFO environments. The Zigbee mesh network tested in this study performed very
consistently and was able to produce message error rates less than 1%. It was also found that the prediction of 125 feet and 2 cage separations was appropriate for this design, which both emphasizes the usefulness of the models developed in Chapter 4 as well as confirms the appropriateness of the selections for safety factor levels. When implemented as a wireless backbone, mesh networking technology will allow for continue addition and manipulation of sensor networks in order to provide a better overall understanding of the dynamic thermal environment within CAFOs.

A case study was also provided to document the potential development and deployment of wireless mesh networking temperature sensors for widespread and dense data collection. It was shown that these nodes could operate for extreme lengths, nearly past the battery expiration interval, and still maintain sampling intervals sufficient for dynamic measurement of CAFO environments. Methods were also documented to directly interface resistive based temperature sensors to wireless nodes, while limiting power consumption through both the sensor circuit and the power supply circuit.
CHAPTER 7

CONCLUSIONS

7.1. SUMMARY OF RESULTS

The results of this work show direct and measurable improvement in the current techniques and methodology of monitoring indoor environment systems in confined animal feeding operations. They will serve as a benchmark for which future advancements in CAFO monitoring will be compared as the international research focus continues to drive intensive monitoring of large confined livestock facilities. They also serve as an example to question the conventional methodology in sampling theory and explore advanced embedded devices for their ability to provide a resolution and dedication not found in conventional measurement.

The development of an embedded vibration sensor to detect the presence of ventilation fan activity provided current and future researchers with an improved method to calculate overall ventilation and emission from high capacity CAFO facilities. Experiments revealed over estimation errors common to the majority of passive ventilation sensors previously in use and a thorough discussion of fan activity sampling revealed the potential for significant overall ventilation errors occurring directly from poor sampling methodology. Requirements were proposed
to limit overall measurement error by minimizing the modulus of fan on-time and sampling time. Ventilation stage configuration also played a significant role in determining the magnitude of ventilation sampling errors. It was found that during temperate Ohio conditions the minimum ventilation stage was the most prevalent component in error measurement for a tunnel ventilated building. Absolute accuracy though will be building specific and dependent on the number of fans per stage as well as the deadband and slope of the control curve between stage settings. Although the vibration sensors did improve the ability to measure fan on-time, they increased the requirements associated with data acquisition in CAFO facilities by requiring a single input channel for each unique fan. To compensate for this increase in data acquisition requirements, sensor networking was considered to reduce data collection overhead, while maintaining real-time sensor access and improving the flexibility of sensor installation.

Controller Area Networks were found to be a viable means to link multiple analog and digital sensors through a multi-master based embedded network. CAN systems provide the flexibility to add additional nodes as new measurement requirements become necessary and allow suitable bandwidth to carry the required bus load for CAFO environment monitoring. Field trials proved successful in transmitting data from multiple individual fan activity sensors, although individual node failures were occasionally present and presented reliability that would be remedied with a commercial implementation of this technology. It was found that signal attenuation was significant as bus lengths increased to a maximum of 600 meters. This attenuation was counteracted by reducing the baud rate of the
communication and allowing for longer bit times. Signal reflection of the individual bits was another major factor of transmission error caused by the mismatch of impedance between the signal wire and the termination resistor. Improvements in reflection were realized by matching precise termination resistor values to the exact line impedance of the transmission wire. While CAN bus systems did provide a single point of communication between the data acquisition system and the sensor network, limitations still existed with respect to expandability and flexibility of sensor placement. For CAN systems, each individual sensor must be located within a near proximity to the physical communication bus. Furthermore, limitations did exist with regards to the maximum bus length that could be used reliably and which could limit future applications of CAN in CAFO systems as the size of CAFO buildings continues to increase.

Wireless sensor networks were evaluated for their potential to act as the data communication network within CAFOs, because of their ability to overcome the limitation of CAN bus systems by providing enhanced flexibility to sensor placement. Fundamental wireless transmission laws were applied to predict the theoretical signal attenuation when placed in high density poultry layer facilities. Because of the significant levels of attenuation predicted, it was determined that mesh networking topologies, with the ability to create communication bridges between each individual point were most applicable to poultry CAFO networks. A series of experimental path loss studies were conducted using a typical pair of mesh networking nodes to better understand the overall path loss within a CAFO environment. Results found many factors including antenna orientation, enclosure
thickness, free space, antenna height, animal cages, and concrete floor separations to all be statistically relevant factors in determining the overall system path loss. It was further found that linear separation within an aisle and number of cage separations provided the highest levels of signal attenuation.

A model was developed to predict the path loss at any point within a poultry layer facility based on the aisle and cage separation terms. After including a second order cage separation term and an interaction term, the model was able to predict 86% of the system variability. The model was further verified by comparing the model results to the experimental results of a similarly designed building. The model was able to produce an average error of -0.7 dB for all combined points. This strong model correlation indicates that the results of this work can be applied to poultry facilities outside of this study that meet some of the same key characteristics, specifically similar cage design and stocking densities. Furthermore, the verification of all theoretical path loss models indicates that when applied to new systems not representative of poultry layer facilities, basic fundamentals can be used to create initial predictions for path loss requirements.

Finally, a full network of wireless mesh network was deployed to evaluate the overall reliability of such sensor networks. When placed in a grid pattern within a CAFO it was found that each node performed as expected when located within range of other wireless nodes. Nodes that were located on the far extremes of the network did show indications of lower reliability levels because of a reduction in the number of available critical paths. The application of this to future network designs indicates that increased sample density is required to ensure multiple critical path
networks for all nodes and to enable a strong backbone of nodes to serve as full power routers. This routing requirement though will dramatically increase the power requirements of each individual node and will lead to serious consideration of permanent wire installations for router nodes.

7.2. RECOMMENDATIONS FOR FUTURE WORK

Although the vibration sensor developed during the completion of this work does enhance the ability of researchers to monitor the activity status of individual fans, it does not provide any indication as to the magnitude of airflow through each individual fan. An additional enhancement to this technology would be to replace the current microcontroller with one which has hardware Fast Fourier Transform (FFT) capabilities. The FFT results of the continuous time vibration signal would provide the power spectrum density of the vibration signal. In theory, the frequency of the maximum power state should coincide with the pulsation frequency of the fan. By calculating this maximum point in real time, the real time fan speed could also be calculated which would provide a more precise quantification of airflow. Furthermore, this function could also be used as an early indicator for fan maintenance problems which reduces the uniformity of building airflow.

An additional improvement in ventilation sensing methodology would be to integrate pressure drop sensing directly into the vibration sensor to improve the localized pressure measurement for individual fans. Commercially available MEMS and piezo-resistive based pressure transducers are available for less than $5 and provide a small form factor which could be directly integrated into the current sensor design. When a single pressure transducer is used to quantify the pressure
drop across an entire wall of a CAFO, the assumption is made that air pressure is
distributed equally through the open medium. In some instances, such as open air
swine finishing barns or cattle feedlots, this assumption is valid. When considering
poultry layer operations though, the environment is quite different with cages lining
the entirety of a facility and often being located only 3 feet from the exhaust fans.
This narrow aisle way along the building does create a restrictive media and will
cause some variation in pressure across the length of the building. The magnitude of
measurement error throughout the building will be directly proportional to the
variability in this differential pressure measurement.

While wireless nodes were shown to be capable of providing a data network
across the entirety of a poultry layer facility, they still did not provide a total wireless
solution. Because the backbone nodes require constant power to relay messages
from end nodes and because the high path loss affects of the building required a
tight density of backbone nodes, a constant power source must be supplied to these
nodes. This can be overcome by generating a network methodology which would
synchronize individual nodes and allow the backbone to enter a standby state when
all end nodes are also in standby. By shutting the entire network down at precisely
timed intervals, the backbone nodes will not provide any message relay during the
off events, but will provide full network access when they return to full operation.
After each successful network transmission, the network must be re-synchronized
to ensure proper timing of the next transmission event.

Additional work will also be required to validate the capabilities of wireless
networks and proposed path loss model in environments that differ from those
evaluated during this study. The production environments for other livestock, which tend to be more open than poultry production, will exhibit improved path loss characteristics, but no quantification to this path loss reduction is currently known. Furthermore, the attachment of the wireless nodes directly to metal fixtures such as gates or pens will cause some level of antenna detuning which will cause additional path loss not seen in the poultry environment.

Communication through multiple buildings was problematic during the current study and will continue to be a source of limitation for the adoption of wireless networks in CAFO monitoring. Buildings encased in steel exterior provide little opportunity for transmission of signals to the outside environment. Methods should be evaluated to determine if external antennas or other non-conventional designs should be used to expand wireless networks past the current transmission ranges. Data compression techniques could also improve the overall data transfer capabilities of wireless networks by reducing the bandwidth requirements in transferring data from a remote location to its final destination.
REFERENCES


IEEE, 2003. Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs). IEEE Standard 802.15.4. The Institute of Electrical and Electronics Engineers Inc., 345 East 47th Street, New York, USA.


APPENDIX A

DIGITAL VIBRATION SENSOR CODE
ACC VAR BYTE
TIME VAR WORD
SEND VAR BYTE
TEMP VAR WORD
MAXACC VAR BYTE
MINACC VAR BYTE
ID VAR BYTE
TEMP = 100
TEMP3 VAR WORD
BATTERY VAR BYTE
TEMP3 = 30
SEND = 0
TIME = 0
ID = 1
I VAR WORD
FREQ VAR WORD
PREV_FREQ VAR WORD
AVERAGE VAR BYTE
diff var byte
PULSES VAR WORD
THRESHOLD VAR BYTE
J VAR BYTE
PROGRAM VAR BYTE

OPTION_REG.7=0
TRISA = %000000111
'ADCON0.0 = 0
ANSEL = %00000110
WPUA.1=1
CMCON0 = %00000011 'A.0 = I/O, A.1 = ANALOG

HIGH PORTC.0
LOW PORTC.0

read 0,THRESHOLD

LOOP:

MAXACC = 0
MINACC = 255

FOR I = 0 TO 5000
  ADCIN 2, ACC
IF ACC > MAXACC THEN
    MAXACC = ACC
ENDIF
IF ACC < MINACC THEN
    MINACC = ACC
ENDIF

IF ACC > AVERAGE THEN
    FREQ = FREQ + 1
ELSE
    if FREQ > 0 THEN
        PREV_FREQ = FREQ
    ENDIF
    FREQ = 0
ENDIF

NEXT I

diff = maxacc-minacc

if (MAXACC - MINACC) > THRESHOLD THEN
    HIGH PORTC.3
    high portc.4
ELSE
    LOW PORTC.3
    low portc.4
ENDIF

' serout2 portc.4, 396, ["Matt Darr"]
'
' SEROUT2 PORTC.4, 396, [12]
' pause 10
' SEROUT2 PORTC.4, 396, [dec maxacc,"", dec minacc,"", dec freq]
' low portc.3

'count PORTC.5, 10000, PULSES

AVERAGE = ((MAXACC - MINACC) / 2) + MINACC
'SEROUT2 PORTC.0, 16468, ["FAN MONITOR ", , DEC MAXACC, 44, DEC MINACC, 44, DEC FREQ, 44, DEC DIFF, 44, DEC AVERAGE, 44, DEC PULSES, 44, 10, 13] '9600 BAUD
'serout2 portc.0, 16780, [254,1,254,2,dec maxacc,"", dec minacc,"", dec freq]
'serout2 portc.0, 16780, [254,192,dec diff,"", dec average]

IF PORTA.0 = 0 THEN ' JUMP TO RESET THRESHOLD VALUE
    GOSUB ADJUST
ENDIF

GOTO LOOP

ADJUST:
    PROGRAM = 0
    LOW PORTC.3
    LOW PORTC.4
PAUSE 1000
FOR J = 0 TO 9
    HIGH PORTC.3
    PAUSE 100
    LOW PORTC.3
    PAUSE 100
NEXT J

HIGH PORTC.3

FOR J = 0 TO 30
    IF PORTA.0 = 1 THEN ‘ACKNOWLEDGE PROGRAM MODE
        PROGRAM = 1
    ENDIF
    PAUSE 100
NEXT J

IF PROGRAM = 1 THEN
    LOW PORTC.3
    FOR J = 0 TO 30
        IF PORTA.0 = 0 THEN ‘ACKNOWLEDGE PROGRAM MODE
            PROGRAM = 2
        ENDIF
        PAUSE 100
    NEXT J
ENDIF

IF PROGRAM = 2 THEN
    HIGH PORTC.3
    PAUSE 500
    LOW PORTC.3
    PAUSE 500
    HIGH PORTC.3
    PAUSE 500
    LOW PORTC.3
    PAUSE 500

WHILE PORTA.0 = 0 ‘RUN ADJUSTMENT PROGRAM
    MAXACC = 0
    MINACC = 255
    ADCIN 1, THRESHOLD
    FOR I = 0 TO 5000
        ADCIN 2, ACC
        IF ACC > MAXACC THEN
            MAXACC = ACC
        ENDIF
        IF ACC < MINACC THEN
            MINACC = ACC
        ENDIF
        IF ACC > AVERAGE THEN
            FREQ = FREQ + 1
        ENDIF
    NEXT I
ENDWHILE
else
  if FREQ > 0 then
    PREV_FREQ = FREQ
  endif
  FREQ = 0
endif

next i

diff = maxacc-minacc

if (MAXACC - MINACC) > THRESHOLD then
  HIGH PORTC.3
  high portc.4
else
  LOW PORTC.3
  low portc.4
endif
wend

write 0, threshold

for j = 0 to 1
  HIGH PORTC.3
  pause 500
  LOW PORTC.3
  pause 500
  HIGH PORTC.3
  pause 500
  LOW PORTC.3
  pause 500
next j

endif
return

end
APPENDIX B

WIRELESS MESH NETWORKING TEMPERATURE SENSOR

DATA LOGGING C++ CODE
This application starts by initializing the filesystem code. If it succeeds, the LED will flash once and then remain on. If all succeeds, the application then opens a file called 'dataXX.txt' (where XX in filename increments.. creating a new file every time the program is run).

- Writes the entire GPS string into the open file.
- SER1 - RS-232 port for GPS connection, 9600 baud, N, 8, 1 operation.

```
#include <stdlib.h>
#include <stdio.h>
#include <string.h>
#include <ae.h>
#include <ser1.h>
#include <fileio.h>
#include <dos.h>
#include <aeee.h>

/************************ SERIAL PORT DEFINES *****/
#define MAXISIZE 1024 // Buffers for serial communications.
#define MAXOSIZE 1024
#define BAUD 9 // baud rate 9600
#define MAX_GPS_LEN 80 // Assuming GPS string < 80 characters.
#define MAX_scale_LEN 100 // Assuming Scale string < 20 characters.

unsigned char ser1_in_buf[MAXISIZE];
unsigned char ser1_out_buf[MAXOSIZE];
extern COM ser1_com;
//COM* c1;
unsigned char baud;

//wkday,year10,year1,mon10,mon1,day10,day1,hour10,hour1,min10,min1,sec10,sec1
unsigned char time_now[13]={7,0,7,1,0,0,7,1,5,2,0,0,0}; //
char realtime[13];
int rtc1337_rd(TIM* r);
unsigned char rtc1337_rds(char* realtime);
unsigned char r_rd(void);
int r_out(unsigned char v);
void rtc1337_init(unsigned char* time_now);
```
/***** APPLICATION SPECIFIC DEFINES *****/
#define GPS_STRING "\n$GPGGA"
#define scale_STRING "\n$PTNLAG001,"

struct fs_descrip* filesys_init(void)
{
    struct fs_descrip* l_retval = NULL;
    char filename[FNLEN+2];
    int l_index = 0;

    if (fs_initPCFlash() != 0)
        return NULL;

    while(l_index < 100)
    {
        sprintf(filename, "data%d.txt", l_index++);

        if ((l_retval = fs_fopen(filename, O_WRONLY)) != NULL)
            break;
    }
    return l_retval;
}

void main(void)
{
    char l_serString[MAX_GPS_LEN];
    char ls_serString[59];
    unsigned char l_index;
    struct fs_descrip* l_file;
    char s1[40];
    char temp=0;
    char date[11];
    char time[9];
    int slen;
    int i;
    int log;

    /* Board initialization */
    ae_init();
    s1.init(BAUD,ser1_in_buf,MAXISIZE,ser1_out_buf,MAXOSIZE,&ser1_com);
    pio_init(5, 2); // output
    //pio_wr(5,temp);

    //set initial time on RTC
    //rtc1337_init(time_now); //run once to set clock
/* Initialize PC Flash card. */
if ((l_file = filesys_init()) == NULL) {
    return;
}
delay_ms(100);
led(1);

//PRINT FILE HEADER
fs_fprintf(l_file, "Copyright: Matt Darr, The Ohio State University");
if (l_file->ff_status != fOK)
    return;
fs_fflush(l_file);

//PRINT FILE HEADER
//fs_fprintf(l_file, "DATE,TIME, Max Acc, Min Acc, Acc Freq, Acc Diff, Acc Average,
//Fan Speed Pulses, Total Pulse Time\n");
fs_fprintf(l_file, "DATE,TIME, Node Serial Number, Battery Level (mV), Tx Counter,
Digital Port, ACH0, ACH1\n");
if (l_file->ff_status != fOK)
    return;
fs_fflush(l_file);

/* Now, we're ready */
while(1)
{
    if (serhit1(&ser1_com))
    {
        /* Get GPS String */
        getsers1(&ser1_com, MAX_GPS_LEN, l_serString);
        if (l_serString[1] == 78)
            {
                log = 1;

                // add realtime clock data to the serial string
                rtc1337_rds(realTime);
                date[0] = realTime[3];
                date[1] = realTime[4];
                date[2] = 47;
                date[3] = realTime[5];

                /* Get...*/
date[4] = realtime[6];
date[5] = 47;
date[6] = 50;
date[7] = 48;
date[8] = realtime[1];
date[9] = realtime[2];
date[10] = 44;

time[0] = realtime[7];
time[1] = realtime[8];
time[2] = 58;
time[3] = realtime[9];
time[4] = realtime[10];
time[5] = 58;
time[7] = realtime[12];
time[8] = 44;

for (i = 0; i < 11; i = i + 1)
{
    ls_serString[i] = date[i];
}

for (i = 0; i < 9; i = i + 1)
{
    ls_serString[i+11] = time[i];
}

    for (i = 0; i < 39; i = i + 1)
    {
        ls_serString[i+20] = l_serString[i+7];
    }

for (i = 0; i < 59; i = i + 1)
{
    fs_fprintf(l_file, "%c", ls_serString[i]);
}  
    fs_fprintf(l_file, "%c", 10);  
    fs_fprintf(l_file, "%c", 13);  

//fs_fprintf(l_file, "%s", ls_serString);  
    //fs_fprintf(l_file, "%c", 10);  
    //fs_fprintf(l_file, "%c", 13);
if (l_file->ff_status != fOK)
    {
        return;
    }

fs_fclose(l_file);

/* Flash LED everytime a GOOD string is received */
temp = ~temp;
    led(temp);
    log=0;
    l_serString[1] = 48;
}

t

int rtc1337_rd(TIM* r)
{
    unsigned char n, rtc[0x10];
    start(); // write
    r_out(0xd0); // start write
    r_out(0x00); // Register pointer=0
    stop();

    start();
    r_out(0xd1); // start read
    for(n=0; n<0x0f; n++)
    {
        rtc[n]=r_rd();
//    ack();
    ee_clklo();
    ee_sda0(); // acknowledge from master
    ee_clkhi();
    ee_clklo();
    }
    r_rd();
//    no_ack();
    ee_clklo();
    ee_sda1(); // NOT acknowledge from master
    ee_clkhi();
    ee_clklo();
}
stop();
r->wk = 0x07&rtc[3]; // wk day
r->year10 = (0xf0&rtc[6]) >> 4; // Year 10
r->year1 = 0x0f&rtc[6]; // Year 1
r->mon10 = (0x10&rtc[5])>>4; // Mon 10
r->mon1 = 0x0f&rtc[5]; // Mon 1
r->day10 = (0x30&rtc[4])>>4; // Day 10
r->day1 = 0x0f&rtc[4]; // Day 1
r->hour10 = (0x30&rtc[2])>>4; // Hour 10
r->hour1 = 0x0f&rtc[2]; // Hour 1
r->min10 = (0x70&rtc[1])>>4; // Min 10
r->min1 = 0x0f&rtc[1]; // Min 1
r->sec10 = (0x70&rtc[0])>>4; // Sec 10
r->sec1 = 0x0f&rtc[0]; // Sec 1
return(0);
}

unsigned char rtc1337_rds(char* realTime)
{
    int n;
    unsigned char rtc[0x10];
    start(); // write
    r_out(0xd0); // start write
    r_out(0x00); // Register pointer=0
    stop();

    start(); // read
    r_out(0xd1); // start read
    for(n=0; n<0x0f; n++)
    {
        rtc[n]=r_rd();
        // ack();
        ee_clklo();
        ee_sda0(); // acknowledge from master
        ee_clkhi();
        ee_clklo();
    }
    r_rd();
    // no_ack();
    ee_clklo();
    ee_sda1(); // NOT acknowledge from master
    ee_clkhi();
    ee_clklo();
    stop();
realTime[0] = 0x30+(0x07&rtc[3]); // wk day
realTime[1] = 0x30+((0x0f&rtc[6]) >> 4); // Year 10
realTime[2] = 0x30+(0x0f&rtc[6]); // Year 1
realTime[3] = 0x30+((0x10&rtc[5])>>4); // Mon 10
realTime[4] = 0x30+(0x0f&rtc[5]); // Mon 1
realTime[5] = 0x30+((0x30&rtc[4])>>4); // Day 10
realTime[6] = 0x30+(0x0f&rtc[4]); // Day 1
realTime[7] = 0x30+((0x30&rtc[2])>>4); // Hour 10
realTime[8] = 0x30+(0x0f&rtc[2]); // Hour 1
realTime[9] = 0x30+((0x70&rtc[1])>>4); // Min 10
realTime[10] = 0x30+(0x0f&rtc[1]); // Min 1
realTime[11] = 0x30+((0x70&rtc[0])>>4); // Sec 10
realTime[12] = 0x30+(0x0f&rtc[0]); // Sec 1
realTime[13] = 0; //End of string
return(0);

unsigned char r_rd(void)
{
    unsigned char j, k, v;
    k=0x80; v=0;
    outport(0xff72,inport(0xff72)|0x0800); /* Set PDIR0 P11 input */
    outport(0xff70,inport(0xff70)&0xff7ff); /* Set PIO0 P11 input */
    for(j=0; j<8; j++)
    {
        ee_clklo();
        ee_clkhi();
        if( inport(0xff74)&0x0800 ) v = v|k;
        k=k>>1;
    }
    return(v);
}

/***************************************************************************/
/* out byte and return acknowledge bit                               */
/***************************************************************************/
int r_out(unsigned char v){
    unsigned char i, j;
    j=0x80;
    for(i=0;i<8;i++){
        ee_clklo();
        if(v & j){
            ee_sda1();
        }
        else ee_sda0();
    }
void rtc1337_init(unsigned char* time_now)
{
    int i, j;
    start(); // write
    r_out(0xd0); // start write
    r_out(0x00); // Register pointer=0

    i = 0x0f & time_now[12]; // sec1
    j = (0x07 & time_now[11])<<4; // sec10
    i+=j;
    r_out(i); // ptr=0, Enable Sec10, Sec1

    i = 0x0f & time_now[10]; // min1
    j = (0x07 & time_now[9])<<4; // min10
    i+=j;
    r_out(i); // ptr=1, Enable Min10, Min1

    i = 0x0f & time_now[8]; // hour1
    j = (0x03 & time_now[7])<<4; // hour10, 24 hr per day
    i+=j;
    r_out(i); // ptr=2, Enable Hr10, Hr1

    i = 0x07 & time_now[0]; // Wk Day, 1-7
    if(i==0) i=7;
    r_out(i); // ptr=3, Enable WeekDay1

    i = 0x0f & time_now[6]; // day1
    j = (0x03 & time_now[5])<<4; // day10, 31 days
    i+=j;
    r_out(i); // ptr=4, Enable Day20 of a month

    i = 0x0f & time_now[4]; // month 1
    j = (0x01 & time_now[3])<<4; // month 10, 12 month

i=i+j;
r_out(i); // ptr=5, Enable Month.

i= 0x0f & time_now[2];     // year 1
j= (0x0f & time_now[1])<<4; // year 10, 0-99
i=i+j;
r_out(i); // ptr=6, Enable Year xx01

r_out(0x80); // ptr=7, A1M1
r_out(0x80); // ptr=8, A1M2
r_out(0x80); // ptr=9, A1M3
r_out(0x80); // ptr=a, A1M4
r_out(0x80); // ptr=b, A2M2
r_out(0x80); // ptr=c, A2M3
r_out(0x80); // ptr=d, A2M4
r_out(0x01); // ptr=e, Control A1IE=1
r_out(0); // ptr=f, Status
stop();