

2016-01-01

High Fidelity Localization and Sensing for Cattle Analytics

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HIGH FIDELITY LOCALIZATION AND SENSING FOR CATTLE ANALYTICS

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Master's Program in Computer Engineering

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2016

Dedication

I would like to dedicate this thesis to all the people that have helped me through my career to achieve this goal. Firstly, my parents, who gave me everything I needed, supported me the entire way and pushed me to always try for the best and never settle with less than what I am capable. To my grandfather, who set me on this path from early on and made everything easy by making me enjoy learning. To my girlfriend, who helped me stay focused, supported me on all the long nights and made me happy even through the hardest times. To Dr. Eric MacDonald, who helped me develop academically and professionally. And finally, to all my friends and people along the way that helped me in one way or another through this long journey.

HIGH FIDELITY LOCALIZATION AND SENSING
FOR CATTLE ANALYTICS

by

LUIS CARLOS BAÑUELOS CHACÓN, B.S.E.E

THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at El Paso
in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Computer Engineering
THE UNIVERSITY OF TEXAS AT EL PASO

May 2016

Acknowledgements

I would like to thank Rancho El 17 cattle ranch in Hermosillo, Sonora for the guidance in the industrial aspects of this research (<http://www.ranchoel17.com>). The research presented here was performed as a result of funding in part from CONACYT México in the *Programa de Estimulos a la Innovación, Desarrollo Tecnológico e Innovación 2015* with grant ID 221285 and entitled “*Sistema inteligente comerciable para engorda y monitoreo de ganado bovino vía Internet de las Cosas*”. All statements of fact, opinion, or analysis expressed are those of the authors and do not reflect the official positions or views of the funding agency.

I would also like to thank the W.M. Keck Center for 3D Innovation for providing machinery and advise on the 3D printing of our prototype enclosures.

Abstract

Global beef production is projected to reach approximately 60 million tons in 2015 and opportunities to increase efficiencies are significant with recent advancements in remote sensing. By economically monitoring the location and conditions of a herd such as feeding patterns, body temperature, heart rate, and other biometric information, the herd performance can now be enhanced through data-driven optimization. Next generation sensors provide high fidelity data on a wide range of measurable properties, and simultaneously, the wide adoption of these sensor systems in many consumer applications is leading to commoditization and reduced cost due to the associated economies of scale. Deploying sensors in feedlots requires overcoming many challenges including harsh environments (temperature, UV exposure, wind, rain), the presence of substantial cattle mass (affecting wireless communications), battery lifetime, and destructive animal behavior (potentially damaging instruments). This paper describes a framework for economically collecting high volume, high quality data on a wide range of conditions of individual head that can be leveraged to draw inferences about the dynamic behavior of the herd. A ruggedized Bluetooth cattle halter platform has been implemented the Radio Signal Strength Indicator (RSSI) of which was used for triangulation. Implementation of a proprietary antenna was required in order to provide high fidelity distance measurements as required for precise triangulation. The antennas were durable, held in position reliably on the halter and provided an isotropic radiation pattern as required to measure distances accurately from all directions. A correlation coefficient of $r^2 = 0.82$ has been measured between signal strength and distance in all directions as required for high resolution cattle location. The Bluetooth SPI interface can be leveraged to wirelessly relay a wide variety of additional sensor measurements to a central computer from a number of feedlots the number of which can easily scale. Access to unprecedented quantities and qualities of herd data can be leveraged to dramatically improve operational efficiencies and realize precision agriculture.

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Chapter 1: Introduction

The beef industry is one of the largest purveyors of food world-wide and is growing annually [USDA 2015]. With recent advances in sensors and inexpensive wireless communications, many environmental properties are now measureable and accessible at low cost. Operational efficiencies of the feedlot industry can be significantly improved through optimization with advanced analytic techniques given the recent access to high fidelity sensor information (Foulkes *et. al.*, 2015); however, there are many challenges in the collection of data including the expense per cow, the overhead expense per lot, the harsh environment, battery lifetime, animal behavior as well as the amount and fidelity of the measured information. This work focuses on addressing all of these challenges specifically in the context of the cattle feedlot industry and proposes an effective framework for data collection, which has been demonstrated with experimental results.

The proposed platform leverages commodity electronics that are inexpensive but that must be enhanced for the unique requirements of feedlot application. The proposed enhancement increases the quality of the measured distance data in order to be applicable for precise localization necessary in cattle analytics. Bluetooth is a radio protocol originally developed for Personal Area Networks (PAN) in which devices can be inexpensively interconnected such as headsets and keyboards (Bluetooth 2004). The signal strength of Bluetooth can be used to infer the distance between two radios and the protocol also provides significant data bandwidth for short distance point-to-point communication required to transfer other sensor measurements. Through triangulation calculations, the location of individual cattle in a reasonably sized lot can be determined with sub-meter accuracy along with other sensor data from the halter, all of which can be transmitted to a central location for analysis. Collectively, many feedlots can be monitored separately and a second overarching communication protocol – ZigBee – was required to provide the necessary bandwidth and reliability to deliver the large volume of aggregate data. ZigBee is a less popular consumer standard for PANs but provides both longer transmission distances as well

as improved reliability based on the use of self-configuring mesh networks – where data can be relayed from node to node until arrival at the final destination even if some nodes become temporarily non-functional.

The cattle industry stands to be revolutionized by leveraging data analytics in conjunction with the collection of previously unavailable data about individual head of cattle across a herd in large ranching operations. The identification of broad trends such as sources of feedstock that provide better herd performance as well as determining the individual health and well-being of any specific head of cattle in a proactive manner will lead to unprecedented levels of efficiency in the beef industry (Nadimi *et. al*, 2008) (Owen-Smith *et. al*, 2013) (Gaillard *et. al*, 2010) (González *et. al*, 2008) (Anderson *et. al*, 2013) (Anderson *et. al*, 2012).

Chapter 2: Previous Work

Previous research was reviewed that focused on high-fidelity localization systems specifically for areas no larger than 10 by 30 meters (with eight receivers) and in the context of two important additional requirements: (1) maintaining a total cost of no more than \$5 USD per cow while (2) delivering sub-meter accuracy. Given the recent availability of inexpensive electronics capable of measuring the required data, the previous work is limited but research interest is expected to increase exponentially.

Low cost commodity Bluetooth systems generally are equipped with small, inexpensive antennas implemented either as inverted “F” patterns fabricated as plated trace in the printed circuit board or as a chip. These antennas do not provide isotropic propagation patterns (equal radiation strength in all directions) and thus are limited in terms of localization applications as the distance measured between a receiver and transceiver in these anisotropic cases is directionally dependent (Zhoa *et. al.* 2005). Consequently, a review was completed of low cost, small durable antennas – well suited for the feedlot environment, which also provide even radiation patterns. Finally, the communications architecture beyond localization capabilities also provides significant bandwidth to transfer additional sensor data as well. Consequently, previous work of inferring animal behavior based on acceleration data is also included with the understanding that other types of sensors could be integrated into the proposed framework in future work.

2.1 LOW COST, HIGH FIDELITY LOCALIZATION

A review of contemporary localization techniques was completed to identify an approach that satisfied all project requirements. Localization includes two steps: (1) collecting distance measurements of the tag/beacon from a collection of fixed receiver locations or landmarks and (2) numerically solving the estimated position of the tag/beacon in a fixed coordinate system. Although a wide range of sensory information can be used to measure distance between two elements, the cost ceiling of \$5 USD per head and required accuracy limited the possibilities to wireless approaches, which include Global Positioning Systems (GPS), Radio Frequency

Identification (RFID), Radio Signal Strength Indicator (RSSI), Angle of Arrival (AoA) and Time of Arrival (ToA) techniques (Van *et. al*, 2007) (Vorst *et. al*, 2008) (Hoene *et. al*, 2008). The selection was driven by identifying which technique was best suited to leverage commodity-based consumer electronics yet still provide sufficient spatial resolution for utility in cattle informatics.

The following sections describe methods for determining distance between two objects, one of which is a landmark. With distances to three known landmarks location can be determined through triangulation, the method of which it is described later in this section.

2.1.1 Global Positioning System (GPS)

The Global Positioning System uses a network of 24 satellites orbiting the Earth where each broadcasts a signal that includes the satellite's current time and position (Gezici *et. al*, 2005). A receiver listens for these signals and compares the time of arrival and the time of transmission to calculate the time of flight. Time of flight data from a collection of satellites can then be used to calculate a three dimensional position. A standard GPS implementation without enhancements achieves a 15-meter accuracy and by implementing a network of fixed, ground-based reference stations, differences between the reported position of the satellite and actual position of the satellite can be calculated. This correction factor is then broadcasted to receivers, which can correct their calculation in order to achieve 3 – 5 meter accuracy (Hofmann-Wellenhof *et. al*, 2013). Moreover, GPS systems, while considered generally low power electronics, are not suitable for applications that must operate for nine months on a single battery cycle as synchronization and long range communication with satellites is required and consequently, GPS was not considered applicable to cattle analytics based on the spatial resolution and battery lifetime specifications.

2.1.2 Radio-Frequency Identification (RFID)

An RFID system consists of an RFID tag with a unique identifier that can be wirelessly read and two types of tags exist: (A) passive tags harnessing energy from the field produced by the reader and activating only during the read operation, and (B) active tags with a local power source that can operate more sophisticated electronics continuously at a larger range. Passive tags

do not require a battery, can operate for a virtually unlimited duration and have a range of typically two meters. While active tags have the advantage of increased range, passive RFID systems with an array of relatively expensive readers can identify object location by reading the inexpensive tags and exploiting the short range to determine if the object is adjacent to one or more readers in the array (Sanpechuda *et. al*, 2008). The resolution given by such a system is limited to mapping the visibility of the tag to the readers at predefined location, as there is no signal strength indication. The system also lacks two-way communication, required for configuration and additional sensory data collection. The restricted range of measurement, the expense of the large number of readers and the lack of auxiliary data transmission eliminated the use of RFID for cattle analytics.

2.1.3 Ultra-Wide Band (UWB)

A UWB system works by sending short pulses (< 1 ns) with a low duty cycle (1;1000) where the signal is transmitted over multiple bands simultaneously at frequencies from 3.1 to 10.6 GHz (Gezici *et. al*, 2005). A set of fixed receivers calculates the Time of Flight (TOF) from the received pulses or alternatively the Angle of Arrival (AoA) by observing the TOF difference between multiple antennas. The short duration of the pulses allows for easy filtering of duplicate multipath signals generated from reflections and the typical accuracy of UWB systems approaches 20 cm while operating without interference in proximity of other RF systems; however, in contrast with other RF technologies, UWB is not prominent in consumer electronics, requires both local synchronization (McCrary *et. al*, 2000) and custom designed circuits to measure location for a given application. Consequently, UWB was considered too expensive for cattle analytics due to the custom design and requirement for precise synchronization.

2.1.4 WLAN (IEEE 802.11)

The IEEE 802.11 standard implements mid-range wireless local area network with the 2.4 GHz Industrial, Scientific and Medical (ISM) band. 802.11 Wi-Fi is the most prominently implemented in wireless networks around the world and the capability of which is included in most personal computers and mobile devices. The wide adoption of this standard for communication

provides economies of scale for localization applications. The RSSI (Received Signal Strength Indication) can be used to measure the distance from an object to the access point. With multiple access points, the position can be calculated (Honkavirta *et. al*, 2009). However, multipath propagation from reflections, signal absorption by obstructing solid bodies and anisotropic antennas induces errors in the RSSI and resolution has only been optimized to 2-3 meters using fingerprinting as demonstrated by Microsoft RADAR (Bahl *et. al*, 2000). Furthermore, although low power, the power required in 802.11 is in excess of the energy budget for the proposed application.

2.1.5 Bluetooth Low Energy

Bluetooth is a wireless standard for short-range communication of mobile devices running in the 2.4 GHz ISM band such as headsets or keyboards. A low energy subset of Bluetooth version 4.0 was introduced for applications requiring sparse communication and long battery life, which implements a (1) lightweight link layer providing low power idle mode operation, (2) simple device discovery by broadcasting short packets periodically, and (3) simple point to point data transfer. As in the case with WLAN, the RSSI measured on broadcast packets can be used to calculate the distance between a receiver and an object (Kotani *et. al*, 2003) (Bahl *et. al*, 2000) (Bandara *et. al*, 2004) (Rodas *et. al*, 2007) (Castaño *et. al*, 2004). Previous work has demonstrated down to two-meter accuracy with a positioning delay of 15 – 30 s using commodity systems with traditional antennas (Wang *et. al*, 2013). Bluetooth was selected with enhancement of a custom isotropic antennas to maintain low cost while providing the required spatial resolution. To improve upon previous work, special attention was paid to minimizing antenna directionality and optimizing the accuracy of the mathematical algorithms for calculating distance in the context of a feedlot.

2.2 ISOTROPIC ANTENNAS

In typical use cases such as mobile devices, keychain and other commodity systems, Bluetooth antenna design focuses on minimizing the size and cost while maximizing the average

range that can be obtained with the lowest possible power. There are two primary antenna designs that dominate the market, monopole and chip antennas – both of which are not optimized to provide repeatable distance measurements between radios but instead to improve the average communication range. (1) Monopole antennas are a version of the standard reference dipole antenna with only a single element. A $\frac{1}{4}$ wavelength element perpendicular to a theoretically infinite ground plane is used. In practical application the element is traced along the ground plane, and the ground plane is provided by the rest of the PCB. For more compact applications, the antenna element can be traced in an inverted F-shape parallel to the ground plane (Whip Antenna) or as an inverted F-shape with the wire folded back and forth on resonant points (Meander Antenna). Folding the antenna reduces the efficiency as the size decreases further. (2) Chip antennas further reduce the volume required by pairing a smaller, more lossy antenna design, such as a highly compressed meander or a helix antenna, with a ceramic package with higher dielectric constant and lower loss than traditional FR4 (glass epoxy used in PCBs). Chip antennas provide a trade-off between size and efficiency – in which both are critically important in small hand-held battery-powered devices. Both antennas provide reasonable efficiency with a typical -3 to -6 dBi loss (efficiency compared to a reference dipole antenna) and a mostly omnidirectional propagation pattern as shown in figure 2-1

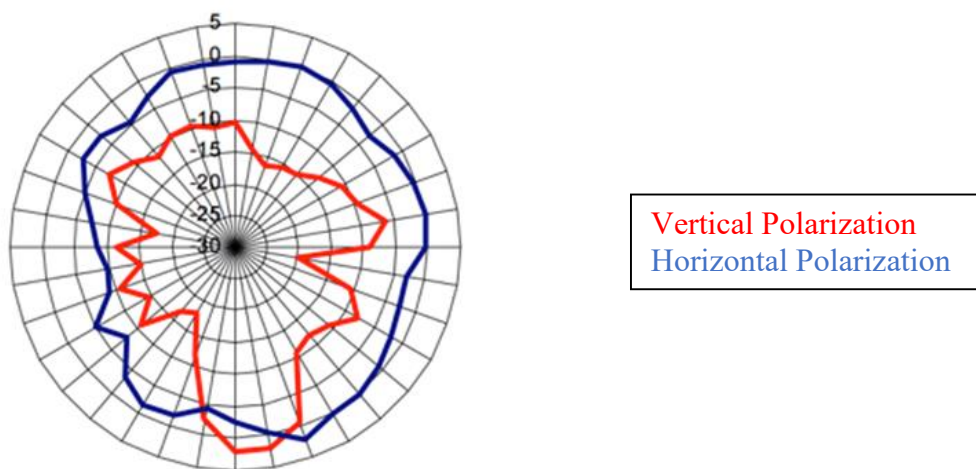


Figure 2-1: Radiation pattern for Inverted F Antenna (Freescale 2015)

However preliminary testing of such antennas for localization showed that the propagation patterns were too anisotropic to obtain repeatable signal strength reading required to accurately measure distance in any arbitrary direction. Since signal strength-based localization depends on a predictable change of the strength given the distance between transmitter and receiver, the antenna must propagate evenly – at least along a parallel plane to ground. A simple dipole antenna can provide the required isotropy – the radiation pattern of which is toroid-shaped about the axis of the dipole. In other words, the radiation is completely even on a plane perpendicular to the antenna. A challenge specific to cattle localization is that the antenna must stand perpendicular to the ground with a length of 8 cm for an antenna operating at 2.4 GHz. Maintaining a stable antenna position and orientation while secured to a cattle halter is difficult and unreliable.

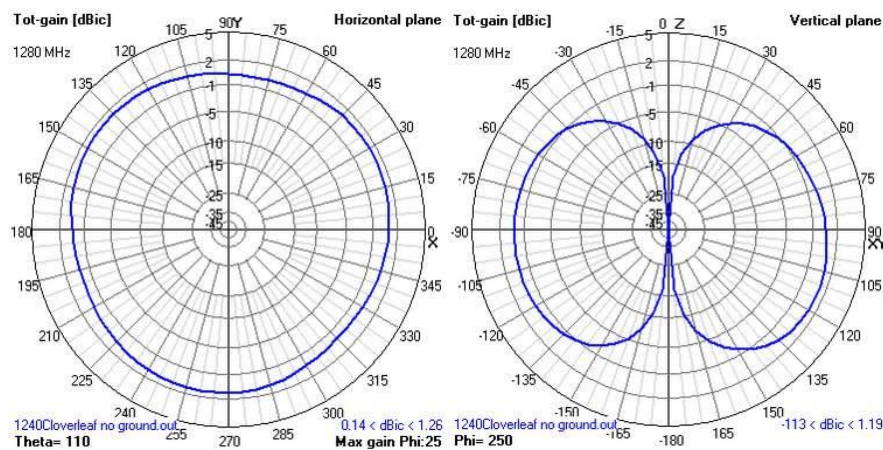


Figure 2-2: Horizontal and vertical radiation patterns of the Cloverleaf antenna (Greve, 2015)

An additional concern specific to distance measurement with RSSI is polarization. With linearly polarized antennas, the signal can reflect off the ground and other surfaces, leading both to constructive and destructive interference on the receiving end. This effect, called multi-pathing, can be beneficial for long range applications as the signal can be received even where no direct line of sight exists. However, the signal strength is prone to fluctuate randomly because of multi-pathing interference. With circular polarization, signals arriving from multipath will be attenuated and thus the effects of this interference reduced. A simple antenna design that meets the

requirements of small size while simultaneously providing even propagation and circular polarization is the three-lobed skew-planar wheel antenna. The antenna is composed of three lobes with relative sizes at $\frac{1}{4}$ wavelength and is often referred to as a “cloverleaf antenna”. The design requires a smaller total package volume than the dipole given the aspect ratio of the height, width and thickness, and can be reliably encapsulated and mounted on top of cattle in the halter. By providing a wire guide with a 3D printed substrate, the small volume of the cloverleaf antennas can be exploited, the weight can be reduced by optimizing the infill of the substrate volume and the wires can be protected from external abuse by routing through internal channels – only possible with 3D printing as the proposed antenna guide could not be manufactured with traditional injection mold processes. The freedom of 3D printing also allowed for the electronics casing to be integrated mechanically with the wire guide antenna and halter mount in a single structure that provided for reliable distance measurements (MacDonald *et. al*, 2014, Espalin *et. al*, 2014, Liang *et. al*, 2015, Shemelya *et. al*, 2015, Lopes *et.al*, 2014).

2.3 DISTANCE CALCULATION FROM RSSI

To use Bluetooth RSSI for measuring distance, a function must be applied to translate the signal strength to distance while dynamically accounting for the fluctuating conditions of the ambient environment. Two formulas were evaluated to compute signal attenuation:

$$rssi = -(10n \lceil \log \rceil - 10 d + A) \quad (2-1)$$

Equation 2-1 is a logarithmic attenuation formula where d identified the distance between transmitter and receiver; while A and n are parameters describing the surrounding environment. A is the absolute energy at one meter from the receiver, and n is the transmission constant. (Wang *et al*, 2013)

$$d = \sqrt[n]{C \frac{P_{tx}}{P_{rev}}} = A \left(\frac{P_{tx}}{P_{rev}} \right)^n \quad (2-2)$$

Equation 2-1 is an exponential attenuation formula which considers two environmental variables where A is constant and n is the information loss coefficient. In addition, receiver power (P_{rev}) and transmitted power (P_{tx}) are considered. (Vorst *et. al*, 2008)

2.4 TRIANGULATION METHOD

Given a collection of distance measurements between a set at least three landmark receivers and the beacon/tag, the position of the tag can be calculated. The *Barycentric* and *Centroid* triangulation technique were implemented to accommodate the probabilistic nature of the distance data input and will be discussed in the experimental section. Figure 2-4 identifies the measured signals and converted to distances as red arrows.

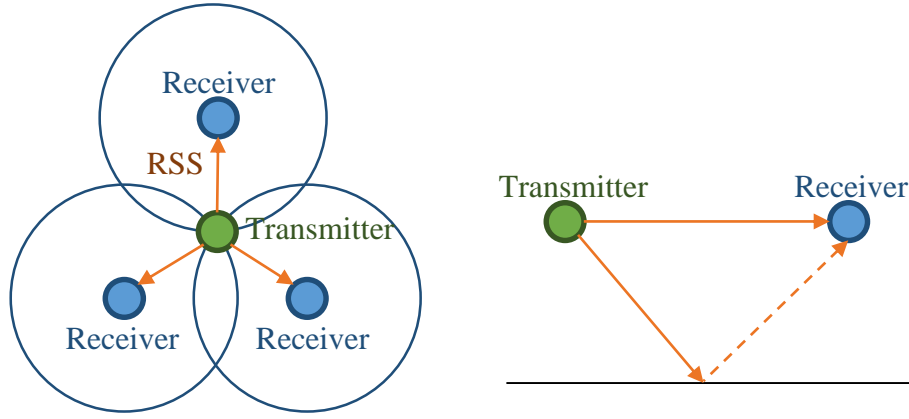


Figure 2-3: Triangulation principle and signal propagation example

Barycentric Location: The Barycentric method obtains the center of gravity from various vertices, the receiving antennas of which have different priority weights. As distance measurements are more reliable for shorter distances (stronger RSSI measurements), closer vertex are afforded stronger weights which attracts the center of gravity and the weights are calculated from the equation 2-3:

$$P_{A_1} = \frac{(d_{A_1})^{-1}}{\sum_1^n (d_{A_n})^{-1}} \quad \sum_1^n P_{A_n} = 1 \quad (2-3)$$

The center of gravity can then be calculated by multiplying the obtained weights by the coordinates from the vertices, as shown in equation 2-4 (Weisstein *et. al*, 2015):

$$Center = (\sum_1^n x_{A_n} P_{A_n}, \sum_1^n y_{A_n} P_{A_n}) \quad (2-4)$$

In the following figure 2-4, four receiving antennas and a transmitter in the central area are considered. Each antenna has a certain distance to the transmitter, representing its inverse weight

divided by its coordinates. The weight of the south-eastern antenna is 43% according to the formula shown in equation 2-5:

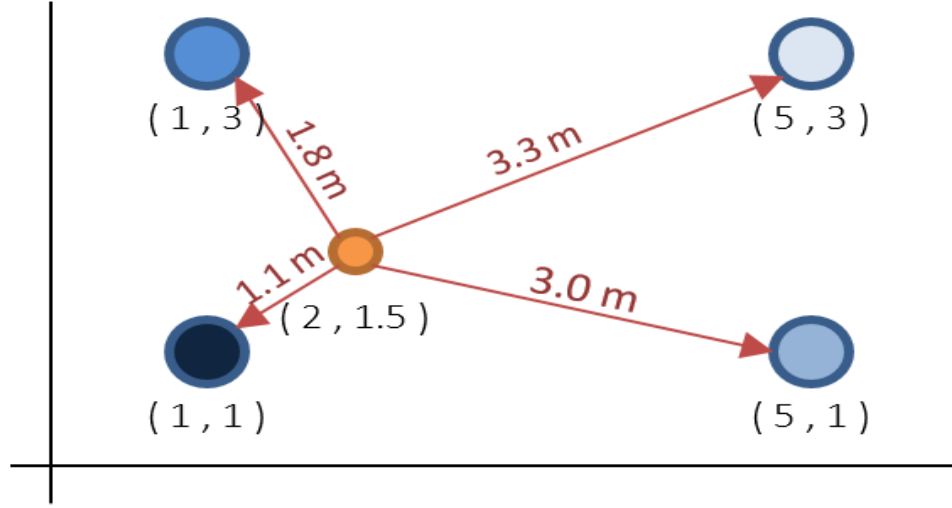


Figure 2-4: Barycentric triangulation example with weighting

$$P_{Ac} = 1.1^{-1} / (1.1^{-1} + 1.8^{-1} + 3.3^{-1} + 3.0^{-1}) = 0.43 \quad (2-5)$$

The rest of the weights are likewise calculated and multiplied by their respective coordinates as shown in table 2-1:

Table 2-1: Estimated position calculated from the obtained weights

Receiver	X	Y	Weight	X (Weighted)	Y (Weighted)
A (northwest)	1	3	26.7%	$1 \times 0.26 = 0.27$	$3 \times 0.26 = 0.80$
B (northeast)	5	3	14.3%	$5 \times 0.14 = 0.72$	$3 \times 0.14 = 0.43$
C (southwest)	1	1	43.1%	$1 \times 0.43 = 0.43$	$1 \times 0.43 = 0.43$
D (southeast)	5	1	15.8%	$5 \times 0.15 = 0.79$	$1 \times 0.15 = 0.15$
Sum				≈ 2.0 (2.2)	≈ 1.5 (1.82)

Centroid location: As shown on the next graph in figure 2-5, each distance measured by the receiver generates a radius. The intersection can be obtained by intercepting various radii and are identified as smaller black dots. This method seeks to obtain the center from these intersections, which are weighted equally. With collection of intersections, the possible range of location of the transmitter can be inferred from equation 2-6 (Wang *et. al*, 2013):

$$Center = \left(\frac{\sum_1^n x_{i_n}}{n}, \frac{\sum_1^n y_{i_n}}{n} \right) \quad (2-6)$$

2.6 ACCELEROMETER AND OTHER SENSOR DATA FOR INFERRING CATTLE BEHAVIOR

While leveraging Bluetooth signal strength for localization, the channel can also be employed to provide low bandwidth communication of other sensor data that can deliver further insight into the performance of the herd. The proposed tags included accelerometers, the analytics of which will be reported in future work with the intent of precisely identifying feeding frequency and duration. Potentially other characteristics such as the general health can be inferred from this acceleration data as well. Previous work of others has demonstrated the use of a wide array of sensory information such as temperature, acceleration, blood oxygen levels, and heart rate all of which provide awareness of the state specifically of each head of cattle (Foulkes *et. al*, 2013). Nothing in the proposed platform precludes or hampers the integration of other sensors in addition to accelerometers and this data collection and analysis will be the focus of future work.

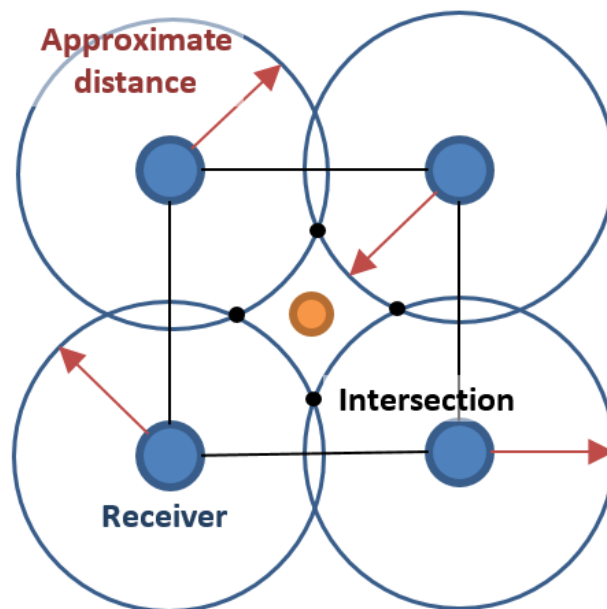


Figure 2-5: Graphical representation of positioning according to the centroid

Chapter 3: Design of the Data Collection and Localization Framework

The architecture was developed based on initial requirements for the system that are not addressed by currently available commercial systems. Additionally, the application was optimized with the intent of scaling easily to a larger number of feedlots in an industrial-sized ranching operation. As of today, the authors are unaware of any data collection frameworks (commercial or otherwise) providing inexpensive data at the scale and precision of the current effort. The potential and type of impact on ranch operation and herd performance were unknown initially and this work is based on the hypothesis that with high volume and quality sensor data for all animals in an operation, a ranch can garner practical information. Decisions can then be improved based on operation-level patterns that guide the enterprise to higher efficiencies both strategically (feed source, calf selection, etc.) and tactically (identify unhealthy / injured cattle, pregnant cattle, etc.).

3.1 SYSTEM REQUIREMENTS

Several characteristics for the framework were identified and prioritized to meet the overall objectives. The overarching goal of the project can be summarized as a data collection system providing:

- (A) *Durability*: The system will include individual sensor beacons, which are required to operate for multiple lifetimes of several animals sequentially. The beacons will be fabricated with the intention of surviving at least two years in harsh environmental conditions and with potential damage due to the natural behavior of the animals. Batteries are assumed to be replaced just prior to attachment to an animal halter.
- (B) *Low Cost*: The system will cost less than \$5 USD per head with other overhead expenses (receivers, repeaters and central computer) amortized into the per-head costs.
- (C) *High Resolution*: Data collection will include high precision sensor information in terms of both: (1) temporal resolution – reporting at least every 10 seconds, and (2) spatial resolution – with less than 1 meter of positional error. Other sensor data will be included in future work and an accelerometer is in the current version of the tag. The

exploration of identifying animal behavior from the accelerometer data is fertile for identifying patterns relating to herd behavior.

- (D) *Low Energy*: The system will include sensor beacons that operate continuously between maintenance cycles in which infrequent intimate access to cattle harnesses is allowed for charging or replacing batteries. Consequently, the beacons must operate unattended for at least nine months – the course of the life of a single animal.
- (E) *Accessibility*: The system will reliably provide all collected data for analysis in a remote office location on a central computer wirelessly.
- (F) *Scalability*: The system will allow for the ease of integration of any number of contiguous feedlots within the operation without concerns regarding communication range or reliability. A feed lot of 10 x 30 meters is targeted now with a maximum of eight receivers per feedlot. However, the feed lot size could be increased with additional receivers and the number of feedlots can be increased given the self-configuring mesh network.

3.2 SYSTEM DESIGN

The framework included designing (1) *sensors beacons* (also referred to as *tags*) required for each head and integrated into the harness and (2) *receivers* where eight receivers were identified as providing optimal Bluetooth localization and sensor data transmission in a lot of no more than 30 meters length and 10 meters width. The receivers also included ZigBee capability for transmission of all aggregate data to the central computer through a reliable mesh network. The beacons were based on commodity system-on-chip electronics (Nordic nRF51822) implemented on a custom Printed Circuit Board (PCB) that included a battery and antenna connection as well as an accelerometer. Figure 3-1 illustrates the sensor beacon board enclosed in a 3D printed casing which also includes an integrated wire guide for the antenna.

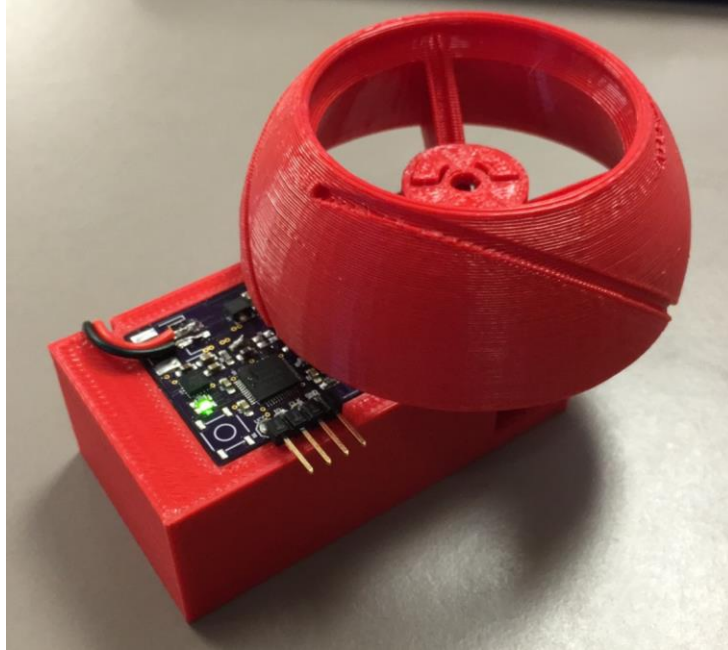


Figure 3-1: Sensor beacon board in 3D printed casing

The beacons can be easily enhanced with more sensors – the data of which can be immediately transmitted or analyzed locally using the ARM processor included in the Nordic radio chip set. Local analysis would presumably reduce the transmission energy; however; the trade-off will be evaluated regarding the reduction of the overall energy depending on (1) local processing with minimized transmission versus (2) complete transmission with remote processing at the central computer. The beacon software was completed on the ARM MBED development platform targeting the ARM Cortex M0 processor – the same architecture as used in the majority of cell phones in use today. Software activity included periodic beacon transmission to the receivers, collecting local sensor data, performing analysis on-board and then transmitting the information to the receiver. A functional diagram of the architecture of the tag is shown on figure 3-2.

The receiver used a standard development hardware kit with both ZigBee and Bluetooth radios and expensive antennas – in which the cost of eight receivers is amortized over the number of head in any given feedlot and consequently is less of a priority to reduce.

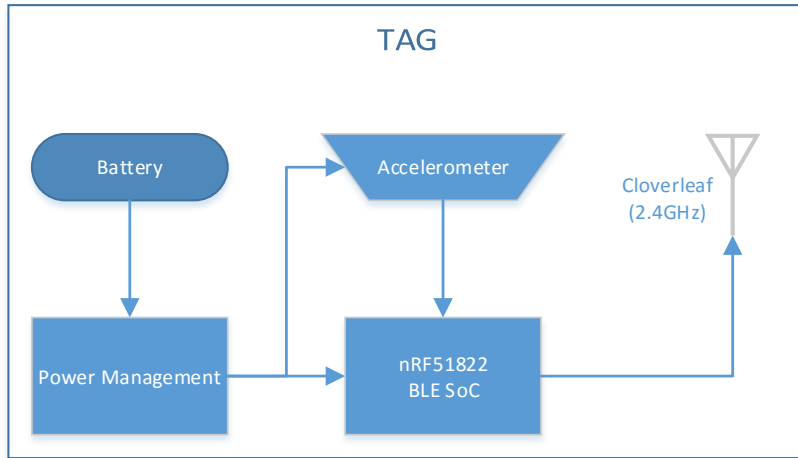


Figure 3-2: Block diagram of the tag/beacon architecture

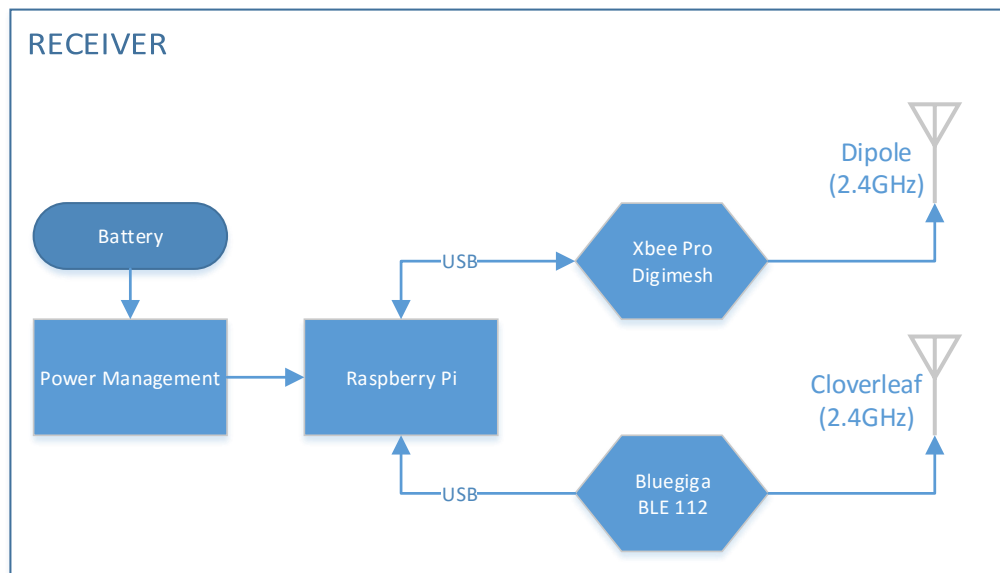


Figure 3-3: Block diagram of the receiver

Figure 3-3 illustrates the basic block diagram showing two antennas – the Bluetooth antenna for signal strength distance measurements of tags as well as any other auxiliary sensor data and the ZigBee antenna for transmitting collected data through a mesh network to a central computer for analysis. As the receiver are statically located, solar panels were used to provide virtually unlimited operational lifetime. Although solar power was generated, batteries were included to provide for data access during the night or when solar was not available.

Software development was completed using Python 2.7 running on a Raspberry Pi with the Raspbian Linux distribution. The receiver software was responsible for aggregating the sensor and localization data, measuring signal strength from each tag and re-transmitting any other received data on the ZigBee mesh network.

3.3 SYSTEM IMPLEMENTATION

The following section justifies the selection of individual subsystems and describes each one in detail. In addition, the electronic and mechanical design is explained.

3.3.1 Tag

The *tag* is composed of three main subsystems: system-on-a-chip, accelerometer and power regulation. Each subsystem works in cohesion to collect, analyze and transmit data, while utilizing the lowest power possible. Careful selection and pairing of each individual component was required to optimize the power budget and obtain the required minimum battery lifetime of six months.

3.3.1.1 System-on-a-Chip (SoC)

The SoC is the primary component of the system. It contains an RF transceiver which communicates with the rest of the system using the Bluetooth protocol, a micro-controller to collect, process and transmit data from sensors, in addition to controlling the state of the system. Such a system allows for minimal power consumption as the internal subsystems can work independently and efficiently. i.e. the transceiver subsystem can periodically send data pre-generated without waking up the micro-controller.

A system with the aforementioned qualities is the nRF51822 by Nordic Semiconductor. The included microcontroller is an ARM Cortex M0, developed primarily for low power applications, with a floating-point unit useful for quickly performing mathematical operations required for running algorithms. The RF transceiver support the Low Energy subset of Bluetooth 4.0 required in the application. An additional consideration was the availability of an open source

toolchain which reduces development costs greatly, in contrast to the IAR Workbench toolchain (\$2,400 USD) required for a similar chip (TI CC2541).

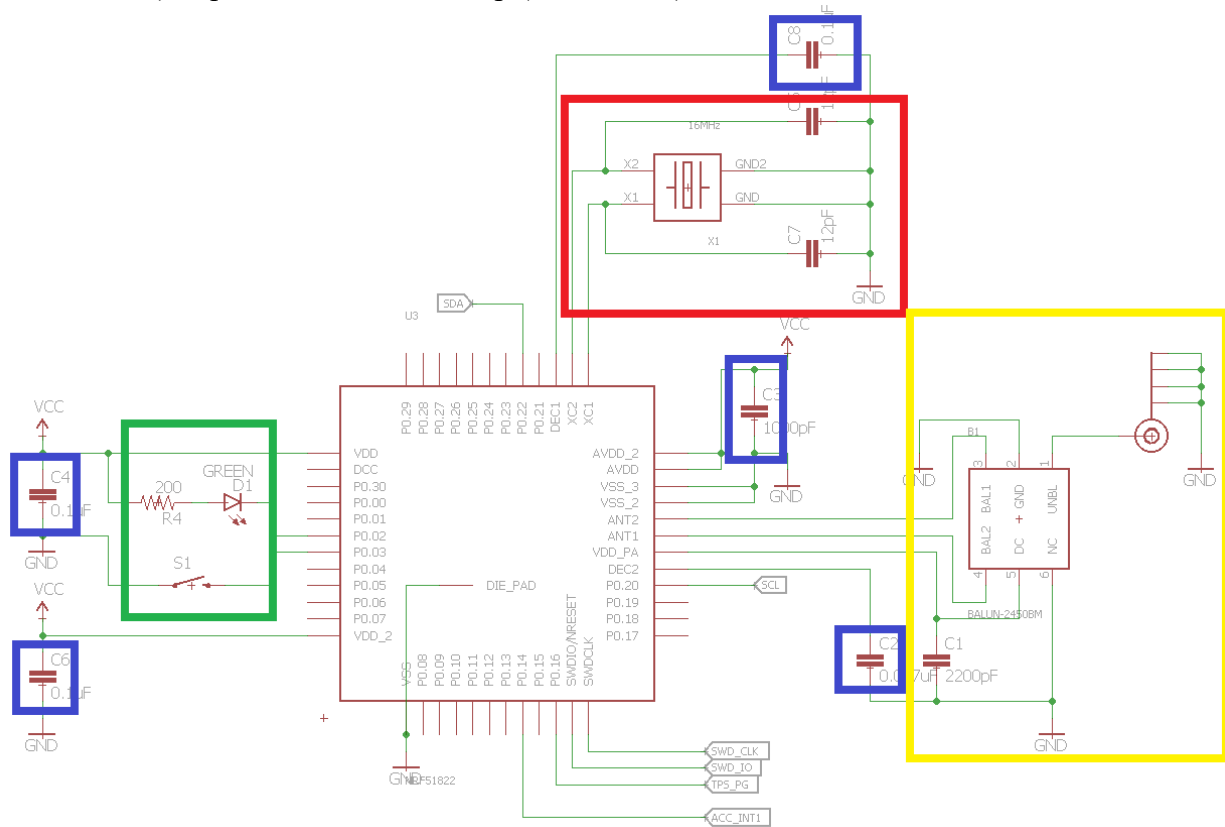


Figure 3-4: Schematic of System-on-a-Chip implementation

Figure 3-4 illustrates the implementation of the SoC along with required supporting circuitry. Enclosed in red is a 16 MHz crystal oscillator, along with 12pF loading capacitors, required to generate the main clock from which the microcontroller and RF transceiver are based. Enclosed in yellow is the RF network to convert the balanced RF signal generated on the SoC to a 50Ω impedance matched unbalanced feed required for the antenna. Enclosed in green are an LED indicator and a push button for debugging purposes. Finally, in blue are the power supply decoupling capacitors to stabilize the power supplied to the microcontroller.

3.3.1.2 Accelerometer

The accelerometer is the primary sensor in the system. The main constraint for selecting an adequate sensor was low power consumption. No other requirements were given as the first prototype is an experimental platform on top of which the algorithm is to be developed.

A Freescale MMA8452Q is a 3-Axis 12-bit digital accelerometer with a selectable range from 2g – 8g, providing a large dynamic range for algorithm development. It communicates over the I2C protocol and has an adjustable rate from 1.65Hz to 800Hz, allowing for very low power consumption (down to 6uA). Another feature, not currently used, is autonomous detection of motion and pulses, useful for gesture controlled operation.

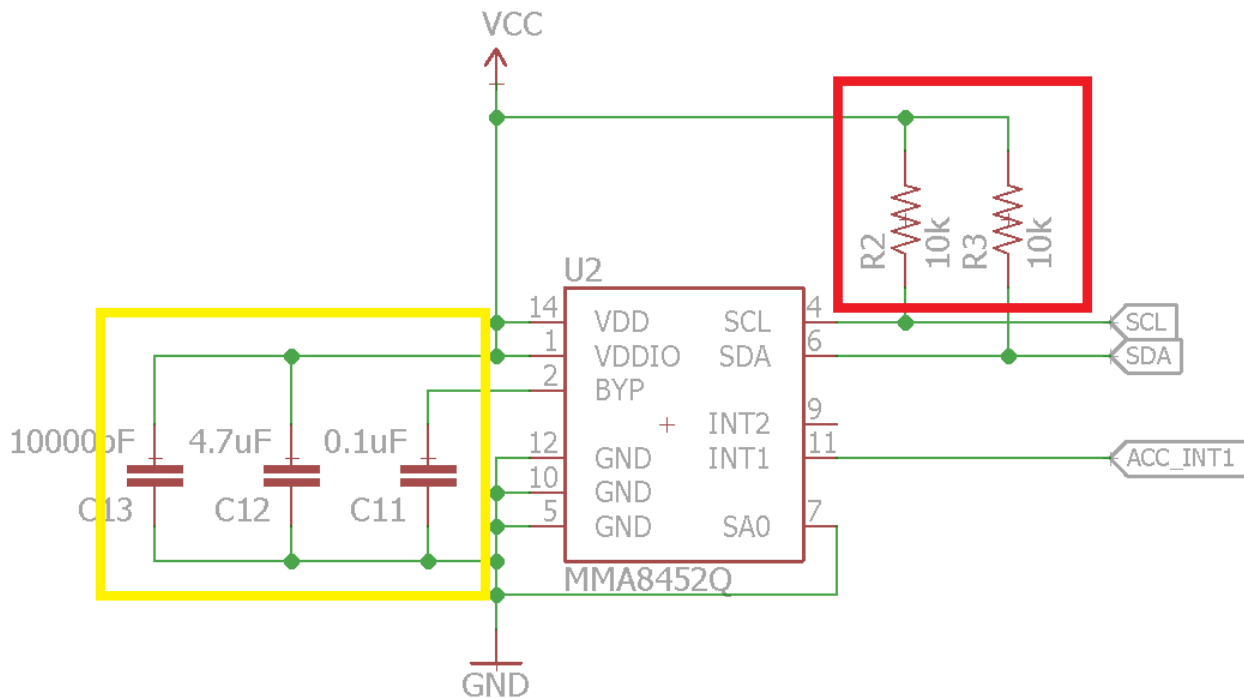


Figure 3-5: Schematic of Accelerometer implementation

Figure 3-5 illustrates the implementation of the accelerometer along with the required supporting circuitry. The I2C bus which the accelerometer utilizes to communicate is an open drain bus, which requires both lines to be pulled up to the supply voltage; enclosed in red are the required

resistors. Enclosed in yellow are the power supply decoupling capacitors to stabilize the power supplied to the accelerometer.

3.3.1.3 Power Regulation

A critical component for low power operation for the device is the power regulator. It must provide a stable power supply to the circuit, while wasting the least possible amount of power in conversion. The metric to classify the efficiency of a power regulator is the quiescent current. This metric indicates the amount of current utilized for operating the regulator.

A regulator with the required properties is the TPS62740 by Texas Instruments. In particular, the regulator is designed specifically for low power wireless applications; with a quiescent current of 360nA. It can also operate on input voltages from 2.2V to 5.5V, allowing operation from a wide range of batteries.

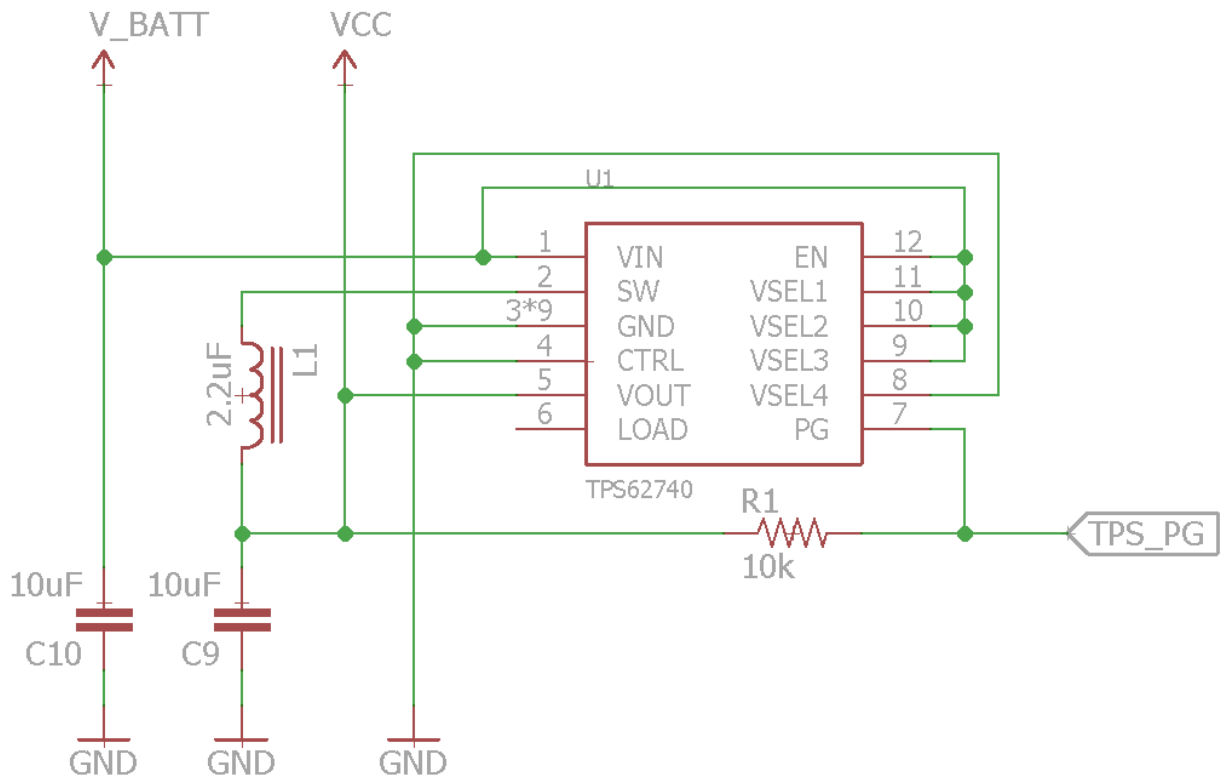


Figure 3-6: Schematic of Power Regulator implementation

Figure 3-6 illustrates the implementation of the power regulator along with the required supporting circuitry. The implementation is based on the reference design provided by Texas Instruments. The device provides four VSEL pins to select the output voltage. An output voltage of 2.5V was selected as the lowest voltage that allows proper operation of all components (of which the LED has a forward voltage of 2.5V). The PG (Power Good) pin provides an indication of when the output voltage is stable and operation can begin, it is tied to an output pin in the microcontroller.

3.3.1.4 Mechanical Design

To date, two different mechanical designs have been implemented. The first design includes a holder for two AA batteries, the printed circuit board, and a custom 3D printed antenna. The modeling was performed in SolidWorks CAD software and 3D printed using a MakerBot Replicator 2X in ABS plastic. However, it is not designed for use in cattle as it does not provide protection to the components it houses. Figure 3-7 illustrates the CAD design and final assembled enclosure.

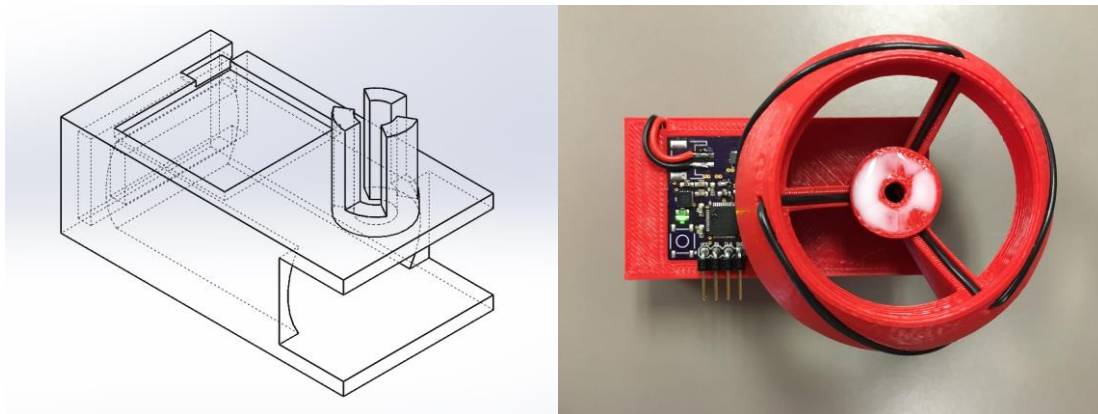


Figure 3-7: Tag CAD Design and Final Assembly

The second design uses a pre-fabricated enclosure rated for outdoor use. This enclosure can host the printed circuit board with a regular wire antenna, in addition to a CR2032 battery holder. Mounting holes are included to mount the enclosure to cattle using a standard halter. The

printed circuit board is fixed to the enclosure using a 3D printed holder. Figure 3-8 illustrates the enclosure, and a circuit board mounted.



Figure 3-8: Pre-fabricated enclosure and circuit board mounting

The enclosure has yet to be tested on cattle.

Chapter 4: Experimental Results

Experiments were designed to evaluate the effectiveness of Bluetooth LE in terms of both measuring distance using RSSI as well as reliably transmitting a relatively high bandwidth of auxiliary information such as accelerometer data. Initial testing was performed with Bluetooth development platform that contained a traditional PCB inverted F-shaped antenna. Due to the highly inconsistent RSSI readings obtained, no correlation between distance and signal strength could be calculated if the direction was changed. The inconsistency was identified as the result of uneven propagation from the F-shaped antenna.

4.1 LOCALIZATION ACCURACY

To identify a suitable antenna for localization, a comparison of a variety of antennas in terms of determining the distance between a beacon and a receiver was performed, four antennas were implemented and the RSSI was measured from a range of angles for a range of distances. This test included evaluating four antennas:

(A) *3D Printed Wire-Guided Cloverleaf Antenna*: A custom, compact antenna well suited for placement on the back of a cattle harness and also providing even omnidirectional, isotropic radiation and circular polarization to reject multipath noise. Figure 4-1 illustrates the antenna in free form (left) and the antenna protected by a 3D printed polymer wire guide necessary providing protection from the harsh conditions of the feedlot (right).

(B) *FXP73 Antenna*: A commercially available relatively inexpensive antenna used by Bluetooth devices for transmission of data with an even radiation pattern and linear polarization. This antenna is optimized for range and designed for market applications requiring a rectangular form-factor and flexibility. A flexible antenna is appealing for cattle because it can stand in its vertical plane and provide optimal propagation. The antenna is shown in figure 4-2 (left).

- (C) *WRL-11320 Antenna*: A commercially available, relatively expensive antenna used by commercial Bluetooth devices for longer distance transmission of data but not optimized for localization applications with RSSI as radiation is somewhat directional. The antenna is shown in figure 4-2 (center).
- (D) *2.4 GHz Half-Wave Dipole Antenna*: A commercially available relatively expensive antenna used by Bluetooth devices for transmission of data but not optimized for localization applications with RSSI. This antenna is used by routers or other high performance networking devices, which require extended range or bandwidth. The antenna provides an ideal propagation pattern and is used as a reference but is not suitable for cattle as the required orientation orthogonal to ground is difficult to maintain above the neck on the halter. The antenna is shown in figure 4-2 (right).



Figure 4-1: Cloverleaf with (right) / without (left) polymer guide



Figure 4-2: FXP73 (Left) WRL11320 (Center) Half-Wave Dipole (Right)

During the evaluation the performance of the four antennas was tested to device which would be most appropriate to use in the localization. The first antenna (A – Cloverleaf) was fabricated with wire and selected based on the omnidirectional behavior and polarization. The greatest benefit of antenna A is the compact, low aspect design and the advantage of the encapsulating geometry creating a wire guide which can be integrated with the additional electronics and into the collar. The next two antennas (B – FXP73 and C – WRL11320) are commercial and are part of the evaluation due to the common implementation. Finally, the last antenna (D – Half-Wave Dipole) was included as a reference. Although inconvenient in form for a cattle harness, antenna D is the standard for isotropic radiation and included for comparison purposes. The test consisted of a single receiver and transmitter in each case, with the transmitter placed at distances from two to ten meters from the receiver, and with zero and ninety-degree angle to test the isotropy of the antenna. Since antenna A is symmetric in every direction, only one test is shown.

Table 4-1: Advertisement packet loss with each antenna

Distance (meters)	A	B		C		D	
	0°	0°	90°	0°	90°	0°	90°
2	1.2%	0.0%	1.6%	1.6%	0.8%	0.8%	0.8%
4	1.2%	0.4%	2.9%	0.4%	0.8%	1.2%	0.8%
6	0.4%	0.0%	0.8%	0.8%	0.8%	0.4%	1.2%
8	0.0%	0.4%	0.4%	0.8%	1.2%	10.4%	1.6%
10	0.8%	0.0%	0.8%	0.8%	0.8%	0.8%	1.6%
12	1.2%	0.8%	0.8%			2.5%	19.5%
Average	0.8%	0.2%	1.2%	0.8%	0.7%	2.6%	4.2%

To verify that no major connectivity was occurring, packet loss was monitored on each test. All antennas successfully received a majority of packets; packet loss only serves as an indicator of link quality, however a small loss does not indicate a problem as Bluetooth advertisements are not acknowledged or guaranteed to be received. As shown in figure 4-3, antenna A approaches a linear regression (a marked correlation between distance and signal strength). All four had challenges beyond six meters of separation. In addition, antennas B and C vary slightly in signal strength and trend pattern with the angle, while antenna A maintained omnidirectionality

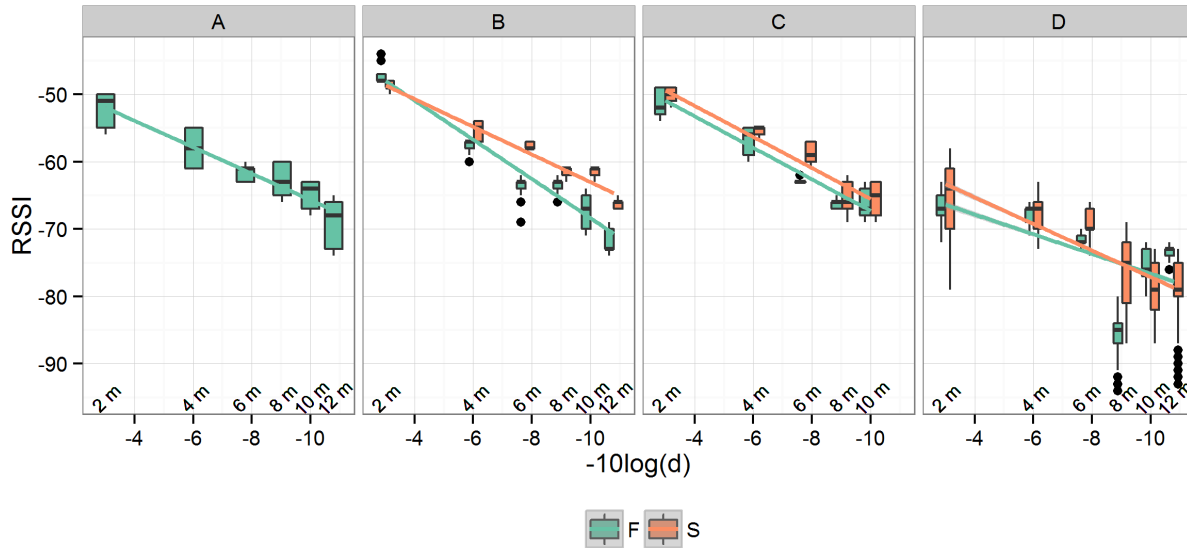


Figure 4-3: Logarithmic comparison of RSSI versus distance

The four antennas obtained good results on a linear regression between distance and signal strength. The best performance was antenna B ($r^2 = 0.95$), followed by antenna C ($r^2 = 0.91$), then antenna A ($r^2 = 0.82$) and finally antenna D ($r^2 = 0.36$). While underperforming compared to antennas B and C, antenna A was chosen for the omnidirectional propagation (same linear regression independent of angle) and the reduced cost based on simple wire and guide fabricated with 3D printing.

4.2 TRIANGULATION TESTING

After identifying the best antenna to correlate distance and signal strength regardless of angle, a triangulation test was performed. The test considered of four receivers placed on a square field with ten meters between each pair, and a transmitter placed at five positions within the polygon shape defined by the receivers as shown in figure 4-4. Each device (receivers and transmitter) used the cloverleaf antenna as this antenna was identified as best for the application. By adding four additional receivers the area can be extended to 10 x 30 meters, which was the initial target for feedlot size.

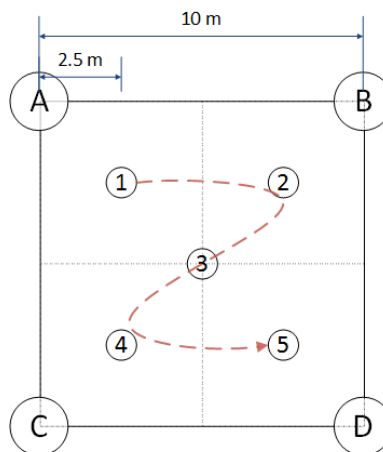


Figure 4-4: Position of receivers and transmitter

An attenuation formula corrects for signal strength measurement errors while translating the received signal strength into an approximated distance from receiver to transmitter. Two attenuation formulas were compared (*logarithmic* and *exponential*) as well as an alternative of *no*

attenuation (linear mapping), in conjunction with two triangulation methods (*barycentric* and *centroid* coordinates). In addition, some percentage of the obtained data was discarded to try and eliminate uncorrelated noise. To ensure reliability, a P-value of 0.9721 confirmed that the obtained data correlates and a strong relationship between distance and signal strength existed. An acceptable correlation between 54% and 87% was maintained as shown.

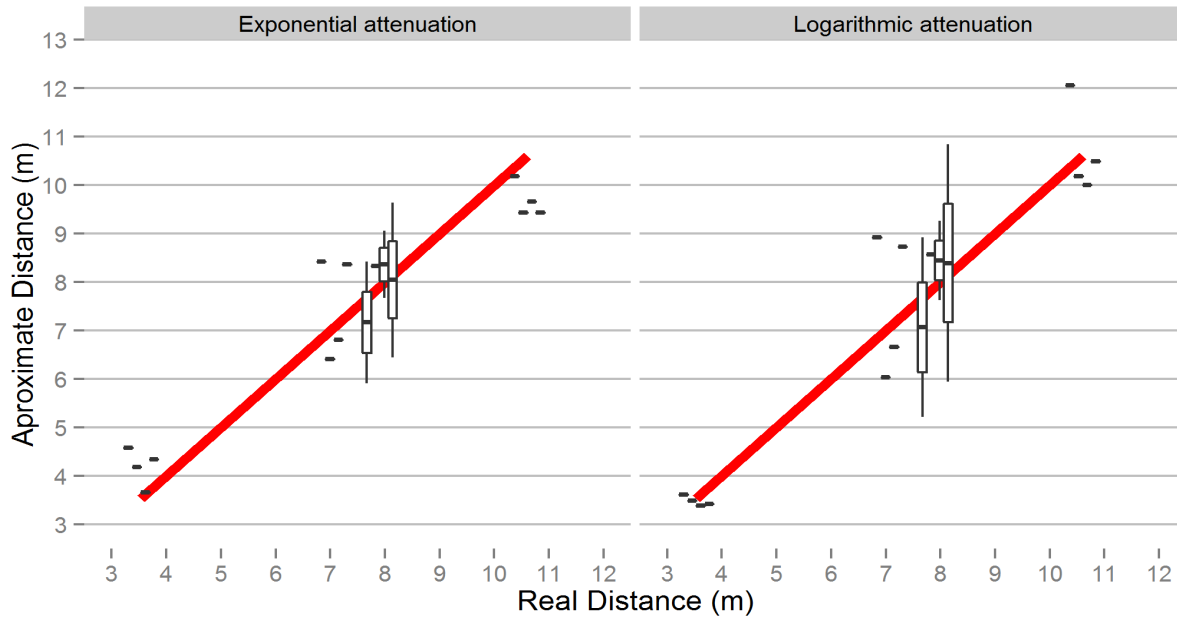


Figure 4-5: The red line represents the actual distance. The box plot shows the distance calculated from each receiver. Exponential attenuation provided less dispersion and was generally more precise.

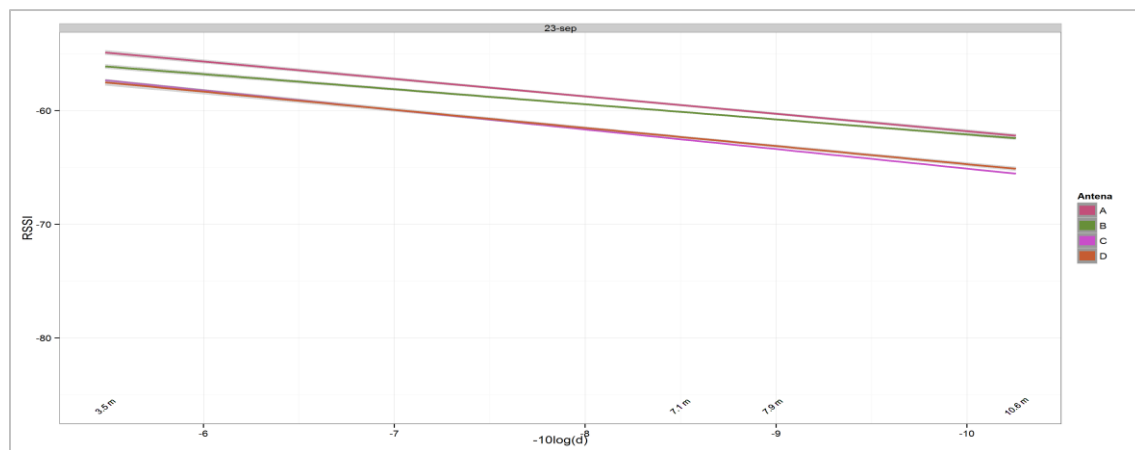


Figure 4-6: A similar relationship between signal strength and distance is obtained on all receivers. This behavior improves triangulation.

To further eliminate inaccurate signal strength measurements, a portion of the outliers in the data set are discarded. First, the optimal percentage of data to average RSSI is determined. Then, the remaining data is discarded to obtain the average RSSI. In table 4-2, the error in meters from triangulation according to discarded data is derived. For each column the best (exponential attenuation and barycentric algorithms) and worst (no attenuation algorithm) average error are selected. Exponential attenuation with barycentric coordinates is shown as the method with smallest average error. Table 4-3 shows the error at each position after discarding 5% of the data (best case).

Table 4-2: Transmitter positioning average error (in meters) depending on percentage of data used for regression. The table shows that the exponential attenuation with barycentric coordinates methods achieves the lowest average error at 1.1753 meters.

% Data discarded	Triangulation methods				
	Barycentric coordinates			Centroid coordinates	
	Logarithmic attenuation	<u>Exponential attenuation</u>	No attenuation	Logarithmic attenuation	<u>Exponential attenuation</u>
0.05	1.2460	1.1343	3.0295	1.4219	1.4055
0	1.2439	1.1385	3.0295	1.3953	1.4268
0.1	1.2511	1.1436	3.0295	1.4183	1.4000
0.15	1.2562	1.1530	3.0295	1.4178	1.3945
0.2	1.2622	1.1627	3.0295	1.3987	1.3875
0.25	1.2708	1.1797	3.0295	1.3118	1.3838
0.45	1.2671	1.2024	3.0295	1.3080	1.3737
0.3	1.2766	1.2047	3.0295	1.3087	1.3797
0.4	1.2694	1.2070	3.0295	1.3062	1.3764
0.35	1.2813	1.2267	3.0295	1.3050	1.3769
Average	1.2625	1.1753	3.0295	1.3592	1.3905

Table 4-3: Table showing the positioning error at the five tested positions with the selected best case from the previous table (5% data discarded)

Position	Barycentric coordinates			Centroid coordinates	
	Logarithmic attenuation	<u>Exponential</u> attenuation	No attenuation	Logarithmic attenuation	<u>Exponential</u> attenuation
1	1.3862	1.3810	3.8290	0.8328	1.6099
2	1.6643	1.0318	3.8017	1.8783	1.6869
3	0.2045	0.2242	0.1184	0.2685	0.1622
4	1.8041	1.9911	3.6887	3.5822	2.4470
5	1.1707	1.0436	3.7099	0.5477	1.1216
Average	1.2460	1.1343	3.0295	1.4219	1.4055

Chapter 5: Conclusions

A proposed framework for supplying high volume, high fidelity sensor data for use in the operation of a large agricultural enterprise has been designed and demonstrated. The ability of a ranch to achieve precision agriculture through advanced cattle analytics is just now possible based on the advancement of inexpensive, commodity networking electronics in conjunction with new and more precise sensors. Collectively, these technologies are providing a refined level of visibility on the operational details of the herd as well as the individual head of cattle in order for ranchers to operate their businesses with improved efficiencies – remotely from the comfort of their home or office.

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Vita

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