ABSTRACT
The Inverse Square Law of Propagation applies to radio waves and gives a mathematical model for determining the intensity of an emitted radio signal at a certain distance from the source. In real life scenarios, however, each environment presents a multitude of interference and multi-paths that make it more difficult to reliably predict the signal attenuation parameters and their distance correlation. Reflection and absorption by physical objects in the environment are two of the many ways, in which the pure mathematical model becomes less robust as a means for determining location. The goal of this project is to conduct an empirical study based on signal strength measurements in indoor environments, using a small number of wireless sensors. By varying the power and distance between sensor(s) and emitter(s), it is possible to generate experimental data that can be analyzed to develop a more robust localization algorithm. For the purposes of this project I will be collecting signal strength data from several emitter(s) and sensor(s) and developing a localization scheme based on radio signal strength. For higher precision localization tasks, such a system may be used to complement location methods such as ultrasound or infrared sensing. The applications of this technology are manifold. It can be used as a method of locating human beings in a building, of tracking employees in an office or of monitoring children at home.

INTRODUCTION
While there are several localization schemes for wireless sensors, this project extends the problem of stationary sensor location and allows for rapid updates of the location of a mobile sensor. The result is a quasi real-time update of the location of a mobile sensor among other wireless nodes. The system also stores the path of the wireless node and can reconstruct the path visually even when the sensor is off. The applications of this technology are manifold. It can be used as a method for tracking the movement of human beings in a building or of locating human beings in an enclosed area. It may be used as an investigation tool since path of a person wearing the wireless sensor is logged and can be reconstructed even after the wearer of the sensor has left the building. It may also be used to guide mobile robots to navigate through a building. There are
also several possibilities of applications in building security such as radio signal intensity triggered security cameras, which would take photographs of approaching people based on the intensity of a radio signal transmitted from a wearable wireless transmitter.

The power management features of the wireless node operating system, TinyOS are also an additional attraction, since the wireless nodes can be kept running for a very long time by dynamically scaling down power consumption when the processor is not being used. For the purposes of this project I will be measuring and calibrating RSSI for the wireless nodes, developing and implementing an algorithm to solve the tracking problem and designing a visual user interface to track and record the motion of the mobile sensor in real time.

INFRASTRUCTURE

Hardware

Mica2 Motes Specification
- 433Mhz RF
- Operate on 2 1.5V AA batteries
- ChipCon 1000 Radio
- 38.4KBit/sec Data Rate FS
- Transmits up to 100ft with 3ft antenna at Max. Power
- Programmed with a Crossbow MIB510 programming board
- 8KB of flash memory

Software

The Mica2 motes are programmed in a NesC, a component-oriented language for networked embedded applications. They run the TinyOS, event-based, low-power use operating system for embedded networks. TinyOS requires less than 400 bytes of memory and is designed specifically for wireless sensor applications.

The Mica2 motes can interface to a PC through a serial cable, to a UART port, which can connect to Java applications via a tool called MIG (Message Interface Generator), which is a protocol for allowing Java
programs to read and write packets through a serial cable to and from the Mica2 Motes.

**Possible Localization Technologies**

**GPS**

GPS has proven to be an effective means of localizing devices around the globe. At the cost of about $100 per receiver, these devices are too expensive to be widely adopted as the localization scheme of choice for cheap, small computing devices. GPS fails indoors and is unhelpful in localizing devices in rooms in a concrete building, for example.

**Ultrasound**

Ultrasound can be used to gather proximity data about sensors and used to localize them relative to each other. It has been widely used in indoor localization of sensors. However, using ultrasound for this localization project would require adding additional hardware and circuitry to the Mica2 motes.

**Radio**

Radio is an attractive localization technology because it is cheap and works indoors. Power considerations also make radio very attractive since the power requirements for a radio transmitter are very small (The Mica2 Mote uses only 16mA to transmit at max. power for example). There is also a well-understood Radio Propagation Model, which can be the basis of a localization scheme.

Additionally, the Berkeley Mica2 motes already have a ChipCon 433Mhz RF transceiver. There need not be any extra hardware costs of mounting ultrasound hardware on the boards.

**Possible Wireless Localization Schemes**

- **Hyperbolic Triangulation**

- **Multilateration**
In **Triangulation**, if a wireless node sends out an RF signal, it is received by the 3 nodes, which send the RSSI data to the base station, which can then triangulate the expected source of the message, or the expected source of the signal. Although this is a fairly simple method, however it is doubtful that it will give very accurate results.

In **Multilateration**, all possible nodes are considered and is therefore likely to be more accurate, albeit more complex and computationally expensive, than hyperbolic triangulation.

**Radio Propagation Model**
The Radio Propagation Model (RPM) explains signal attenuation as distance and other factors are varied. It is the starting point for any localization scheme based on Radio Signal Strength.

### Signal Strength Vs. Distance

![Signal Strength Vs. Distance Graph](image)

Indoors, the signal decays much more rapidly due to obstacles such as walls absorbing some of the signal energy, reflection from obstacles, multi-path ways, diffraction, scattering, refraction and several other interference effects.

It is imperative to collect imperative data from the Mica2 motes and examine whether it follows the radio propagation model and whether it can be used as the basis for a localization scheme indoors.

**Radio Signal Strength Characterization on the Mica2 Motes**

**How does the CC1000 Measure RSSI**
The CC1000 has a built-in RSSI (Received Signal Strength Indicator) giving an analogue output signal at the RSSI/IF pin. When the RSSI function is enabled, the output current of this pin is inversely proportional to the input signal level. Note
that a higher voltage means a lower input signal. The RSSI measures the power referred to the RF_IN pin.

![RSSI voltage vs. input power](image)

**EMPIRICAL ANALYSIS**

**Data Collection and Calibration**

Even though there is a significant amount of (RSSI) publicly available for the mica2 motes, empirical analysis is still important to accurately calibrate the motes used in this project. Several Data Collection experiments are conducted and a description of all the experiments follows in the Empirical Analysis section.

Several wireless nodes are programmed with code that transmits data at regular intervals to a base station, which calculates the mean RSSI of each node over a period of time and logs the data. Before collecting data though, it is important to fully understand how RSSI is characterized on the mote.

**Objective**

Collect RSSI data at various distances and graph the data to determine that it fits the theoretical model.

**The following parameters are varied**

- Vary Antenna Potentiometer value: This regulates the RF transmit power of the sensors. Multiple transmit power levels can be set by varying the Antenna Potentiometer setting, a command which is provided by the mote radio API. The system allows dynamic control of this value from the base PC so that the motes do not need to be reprogrammed each time.
Repeat experiments with different instances of the same device: This helps with calibration and provides a range of values, which can be averaged to get meaningful and reliable data for the motes. This ensures that the location scheme works with all motes and not just a particular set of them.

Vary geography of experimental area: This determines how reliable RSSI data is different areas i.e. in the presence of obstacles, outdoors vs. indoors and at different altitudes of base and receiver.

The following parameters are constant for all experiments.

- Fresh Batteries are used for all motes to ensure that they are all transmitting at the set transmit power
- The antenna height is fixed at 8cm for all motes

With the characterization well understood and the experimental method well defined, measurements can be taken to determine whether the RSSI readings conform to the Radio Propagation Model.

**Calibration**

The Mica2 motes, as for any high-tolerance, low-cost electronic devices, exhibit variation in transmit and receive behavior from mote to mote. Device Calibration is critical in this project because it characterizes and standardizes the behavior of all the wireless nodes being used as either transmitters or receivers. One wants to assert that different transmitters do not send different signal-strength messages to one receiver and that receivers do receive different signal strengths from the same transmitter. More formally, calibration involves conforming a device’s set of parameters $\beta \in R^{p}$, to a calibration function, such that any actual device output $r$ is mapped into the corresponding desired output $r^*$. A calibration function of the following form achieves this object.

$$r^* = f(r, \beta)$$

The variation in the signal strength transmission under idealized settings is an artifact of the radio hardware design parameters, hence the need for calibration. This calibration constitutes the initial phase of the experimentation. The objective of the second phase is to experiment with the behavior of signal strength propagation in indoor environments and devise an algorithm that leverages the existence of multiple signal...
strength levels to make distance predictions using the radio signal attenuation properties.

For the Mica2 motes, there are several possible calibration methods to consider.

**Pair-wise calibration** involves examining each possible transmitter/receiver pair and attempting to fit the response (signal strength measured at a certain distance) to an output function. Because each pair of transmitters and receivers must be examined, this leads to an order \( n^2 \), calibration method.

**Iterative calibration** is where one node is declared as the reference transmitter and used to calibrate all receivers. One node is then selected as the reference receiver and used to calibrate all transmitters.

**Mean Calibration** compares all receivers to the mean of the transmitters and all transmitters to the mean of the receivers. This rests on the assumption that device variations are Gaussian distributed. One collects calibration data for each receiver using all transmitters as calibrating devices. If \( d_{i,j} \) is the distance between receiver \( R_i \) and transmitter \( T_j \) then we have a system of equations for each receiver of the form

\[
d_{i,j}^* = f(d_{i,j}, \beta_i)
\]

which can be solved for \( \beta_i \).

The problem with this method though is that while all receivers (or all transmitters) are calibrated, the transmitters (or receivers) are left un-calibrated and the error of the system as a whole is not minimized.

**Choice of Calibration Method**

We use the traditional pair-wise calibration here since the number of nodes involved in this project is not too large. This calibration method is also very robust and calibrates both transmitters and receivers.

**Experimental Method**

**Notes**
- The data recorded in each of these experiments is the signal strength of the message received, by the receiver, from the transmitting node
- The transmitters send a message every second, yielding 60 data points per minute
The transmit power of the Mica2 mote can be varied within the range 0-255 yielding 5 equidistant transmit power levels.

**Constants**
- Mica2 Motes are used
- The operating frequency of the motes is 433Mhz
- The antenna height is kept at 8cm and is constant on all motes. The antenna height greatly affects the transmit range of the motes.
- All experiments are conducted in the Alcove on the 2nd floor of Watson
- A fully charged set of batteries are used for each TX, RX pair
- Each experiment is thus run for 2 minutes yielding ~120 data points

The following experiments are performed

**Varying the geographical setup**
- RX and TX on floor level, direct line of sight.
- RX and TX on floor level, obstacle in line of sight (obstacles chosen and held constant for these experiments)
- RX and TX at table level (~1m above the ground), direct line of sight
- RX and TX at table level (~1m above the ground), obstacles in line of sight

**Varying Transmission Power**

Explain how you defined the different power levels. Although this is platform specific, it is important for replicating/continuing the experiments later on. A very important parameter that is extremely useful is to find the max range at which radios can still communicate using minimum power, on the ground and when the antennas are elevated. This will provide good information for determining proximity between nodes.

For each scenario above and for each pair of motes 1 and 2, the following experiments are performed

- Node 1 TX at 5 power levels and at 1, 3, 6, 9, 12, 15m away from node 2 RX
- Node 2 TX at 5 power levels and at 1, 3, 6, 9, 12, 15m away from node 1 RX
For each geographical setup, this experiment yields 60 data sets, which are saved to file with a standard naming pattern, described as the following string concatenation

“TX” + Transmitting Node + “RX” + Receiving Node + “P” + Transmit Power Level + “D” + Separation Between RX and TX + “H” + Height above ground

E.g. For Node 1 TX @ 255 and 9m away from Node 2 RX at ground level, this will yield a filename of

TX1RX2P255D9H0

Adopting a consistent naming pattern such as this makes it easy to process the data afterwards.

A java program was written to parse through the data files and collate the data by transmitter, transmit power, receiver or height above ground. This data could then easily be plotted by Matlab to observe RSSI vs. distance.
Does the collected RSSI data confirm the RPM?

**Note:** The RSSI data in the following graphs is inverse i.e. The RSSI values are higher for greater distances. This is an artifact of the way RSSI is measured on the CC1000.
Mote 3 RSSI Vs. Distance at 2/5 Max TX Power

Mote 3 RSSI Vs. Distance at Max TX Power
Mote 4 RSSI Vs. Distance at 2/5 Max TX Power

Mote 4 RSSI Vs. Distance at Max TX Power
The flattening-out of the curves below between about 5m and 9m is due to the fact that beginning at 5m and continuing on, the measurement points were in a narrow corridor. Scattering, diffraction and other interference effects in that region, make it inconsistent with the RPM.

The range of RSSI values as TX power is varied is similar for motes 2-4. The graphs are similar for these motes but mote 5 has RSSI values far below the RSSI values for the other motes. Mote 5 is thus excluded from further experiments.

**Conclusion of Data Collection - The model is inconsistent indoors**

- It is clear that the general trend of RSSI Vs. distance generally follows the expected trend. However, the data does not correspond perfectly with the theoretical model because of multi-path ways, reflection, scattering and other interference phenomena associated with indoor environments. It would thus not yield a reliable localization scheme to naively predict distance using the theoretical model. A new model needs to be devised to accommodate the non-idealities indoors or a new localization scheme needs to be developed.

- There is not enough variation in RSSI values as the transmission power is changed. At Minimum TX power, the Mica2 motes had a range of over 20m. For the purposes of this project, this range is too broad. It was clear from the experiments that the transmission range with an 8cm antenna was too large to be used for the scale of localization I envisaged. There was also little variation in RSSI with Transmit Power also, as is illustrated by the graphs for two motes at different Max TX Power and 2/5 Max Power.

**Solutions**

**RPM inconsistency indoor**

- One approach to dealing with this problem is to separate the localization scheme into two phases - an offline stage in which RSSI data is collected at various locations in a building, and an online stage in which real time RSSI measurements are compared to the data collected in the offline stage to find the closest RSSI, location match. This scheme has been developed at Microsoft in the RADA project. It has shown impressive results, with a median accuracy of 2-3m in a 22\*43m office building.

**TX range variation with TX Power**
The antenna was clipped to about 4cm to provide more variation in RSSI with TX power and to shorten the effective TX range of the motes. An antenna of height 4cm, gives a maximum range of about 3m at the maximum transmit power.

**Brief discussion of Microsoft RADAR project**

**Offline Stage**
Collect RSSI as a function of the users location (red x’s above) from “Base Stations” (blue circles above), which transmit radio signals. This data is used to build a multidimensional RSSI/location lookup table to be used in the online stage.

**Online Stage**
The system performs a multidimensional search through the RSSI database to find closest match to the set of RSSI readings at the unknown location.

**Accuracy of RADAR**
Radar locates sensor to accuracy of a median error distance of 2-3m in a 22m*43m office building

**Disadvantages of RADAR**
- Expensive and painstaking offline stage
- Expensive lookup (in time and computing power) for

**Need to develop a new localization scheme**
Avoids the problems of directly applying the RPM indoors
Avoids the arduous offline stage of RADAR
Avoids the expensive (computational time) lookup costs in the online stage of RADAR

**A novel Localization Scheme**

**Idea**
By using the known transmit range of the Mica2 mote at different power levels, it is possible to establish a bound within which a receiving mote is located.

**Localization**
The overlapping area of these bounds will be the region where the unknown mote must be. The accuracy of this scheme is clearly limited by the size of the overlapping bounded area. We sacrifice some accuracy but reduce huge offline-stage cost of the RADAR approach as well as save on lookup time in the online-stage.

**Transmit Power Ranges**

**A brief note on calibration**
Since this scheme only localizes to a bounded area, it is less sensitive to the small differences between the motes, which would otherwise necessitate a more exhaustive calibration. For this project, I selected motes, which had roughly similar transmit ranges at different transmit powers.

![Diagram illustrating Range Bounds at different TX Power Levels for a Mica2 Mote](image)
The following range data was collected for the motes at the following TX powers:

<table>
<thead>
<tr>
<th>TX Mote</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>75</th>
<th>150</th>
<th>255</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.6</td>
<td>1.0</td>
<td>1.2</td>
<td>1.6</td>
<td>2.5</td>
<td>3.0</td>
</tr>
<tr>
<td>3</td>
<td>0.5</td>
<td>0.9</td>
<td>1.0</td>
<td>1.9</td>
<td>2.6</td>
<td>2.9</td>
</tr>
<tr>
<td>4</td>
<td>0.7</td>
<td>1.3</td>
<td>1.5</td>
<td>2.1</td>
<td>2.5</td>
<td>2.7</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
<td>0.6</td>
<td>0.9</td>
<td>1.4</td>
<td>1.8</td>
<td>2.0</td>
</tr>
</tbody>
</table>

*The CC1000 Radio Transmit Power is scaled from 0-255 arbitrary units corresponding to an output power from –20 to 10dBm

**Localization in 4 simple Steps**
TX nodes (TX1, TX2 and TX3 in the diagram) whose location are known, transmit packets at different transmit power levels. The location of these nodes is known beforehand. Whenever, the unknown-location node (RX) receives packets from the TX nodes, it refers to a database of TX power ranges and constructs concentric regions around each TX node it receives packets from.

**Overlapping concentric regions** correspond to the regions of highest likelihood of containing the RX node.

**A note on accuracy**
This scheme only localizes to a bounded region and cannot give an \( <x, y> \) type localization. Because of the varying ranges between motes at different TX powers, the maximum resolution of the localization scheme is also limited to the maximum range between two TX ranges at a particular transmit power.

**Geography**
The test area is a 3m*3m area on the floor of AKW 000. The area is free of physical obstacles.

**Choice of Antenna**
The antenna height is very critical to the transmit range of the Mica2 mote. The antenna height of the motes is maintained at 4cm which gives enough variation in range as the transmit power level is varied.
**TX Node Pseudocode**

While
- Transmit Packet at Power X
- Select Next TX Power
- Delay for 1 second

**RX and Localize**

The receiver runs the RX program which forwards packets it receives through a serial cable to a Java application running on a laptop. It is on this laptop, that the data is collated and used to localize the unknown-location node.

**RX Pseudocode**

If Receive Packet from a TX Node
- Lookup range of the TX Power
- Draw circle round the TX Node
- Mark the region of greatest overlap with other range circles

**Localize Pseudocode**

Localize
- Mark region of greatest overlap
- This region sets the bounds on the location of the Unknown Node.
Results
The following table shows some results using this localization scheme.

<table>
<thead>
<tr>
<th>Actual Location</th>
<th>Contained in Bounded Region</th>
<th>Obstacles Present</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.4, 0.4&gt;</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>&lt;0.4, 0.4&gt;</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>&lt;0.0, 1.0&gt;</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>&lt;0.0, 1.0&gt;</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>&lt;0.0, 2.0&gt;</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>&lt;0.0, 2.0&gt;</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>&lt;0.0, 0.6&gt;</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
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<td>Yes</td>
<td>No</td>
</tr>
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<td>No</td>
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<tr>
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<td>No</td>
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</tr>
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</tr>
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<td>Yes</td>
</tr>
<tr>
<td>&lt;2.6, 2.6&gt;</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Note
The <X, Y> co-ordinates correspond to points in the 3*3 test area where <0,0> is the bottom left corner.

Obstacle Tolerance
Even though this scheme is 100% obstacle tolerant, the resolution of the localization falls, as TX motes are “cut-off” by obstacles. If 3 motes are “cut off” by obstacles, an RX mote in the farthest corner of the grid away from
the remaining TX mote is correctly predicted to be in an area close to the size of the entire grid. In such a scenario, the localization is unhelpful and succeeds only in localizing the RX mote into the test grid.

**Screen Shots of Localization Software**
The bounded region of localization is the green region in the following screen shots of the localization software.

1. **Note**
   There are 4 TX nodes in the corners of this grid.

   The accuracy of the localization is highest when all 4 TX nodes are used in the localization.

2. **Note**
   3 TX nodes are used in this localization.

3. **Note**
   3 TX nodes are used in this localization.

   The bounded region is significantly larger than in the other cases because the localization “rings” are larger in this experiment than in the two above.
Conclusion
The localization scheme devised, works. The resolution of the localization is rather high though. The sacrifice for point-type accuracy is a scheme that requires little computation in the online phase to localize the unknown mote. The following improvements would yield a more robust localization scheme.

Refinement
Some form of refinement would improve the accuracy of this localization scheme. Bayesian Filters, Learning algorithms and neural networks are only some of the methods that might be used to achieve better localization. A brief discussion of Bayesian Filters and how they might be used to refine this localization scheme follows here.

3D localization
This scheme localizes only in 2D. It cannot reliably localize motes that are not on the ground level. It is not a trivial exercise to extend this scheme to work in 3D. Conceptually, it is a simple exercise to localize an unknown-location mote, using overlapping concentric range spheres rather than planar circles. However, the difficulty is that the range of transmission will be different at different heights and so it one cannot assume that the range data at ground level is reliable in three dimensions.

One would need to experimentally verify the variance in range above ground level and then devise a scheme to compensate for these differences. At worst, the largest range at in any dimension can be taken as the 3D range at that transmit power, although this would significantly reduces the maximum resolution of the localization.

Bibliography
[1] Pereira, Kevin., “An empirical investigation into a location sensing system based on RF signal strength of TinyOS motes”


