# CS268 Computer Networks
# Localization using Dot3 wireless sensors

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May 16, 2003

**Abstract**

ChipCon radio is the radio chip that has been used recently for wireless sensors in Berkeley NEST group. ChipCon radio generates an analog signal indicating the signal strength of the received data bits and we used this signal strength as a tool for localizing sensor nodes. We modified the network stack of DOT3 sensor nodes to make the signal strength available. Experiments showed that the signal strength can be used to locate sensor nodes, but this required the network nodes to be sparsely located. Since our method uses the signal strength information which is already built in the sensor nodes, it can be easily deployed.

**Key words**: sensor network, localization, radio signal strength, ChipCon radio

## 1 Introduction

Wireless sensors are commonly used for monitoring environment like lighting, temperature, humidity and air pressure. However, wireless sensors can also be used for locating objects. Different methods can be used depending on the accuracy goal and resource limitation. For example, GPS, acoustic signal, magnetic field, radio signal strength and so on. While it is shown that radio signal strength is not as accurate as GPS or ultrasonic method, radio signal strength has the advantage that it doesn't need additional hardware: it comes free with the radio communication. This can be useful when the requirement for accuracy is not high.

Recently, NEST group in UC Berkeley started to use wireless sensor platforms (DOT3 and MICA2) that have ChipCon radio. ChipCon radio has better range (1000 feet vs. 400 feet) and smaller loss rate than RFM radio which was used for earlier version of sensor nodes ([3]). But, application of signal strength of ChipCon radio has not been explored. In this project, we try to find how the signal strength of ChipCon radio can be used for localization.

## 2 Related Works

There are many works for localization in diverse contexts.

Cricket [1] radio and ultrasound to locate a mote. Based on the fact that propagation speeds of radio wave and ultrasonic wave are different, it decides the distance between a beacon node and a listener node by looking at the difference in arrival time of radio and ultrasound. Then using beacon position inference algorithm, it picks the beacon node which is regarded as the closest. Since Cricket uses ultrasound, sensor nodes need to be equipped with ultrasonic transceivers.

RADAR [2] runs on WaveLAN. In *Empirical Method*, preprocessing is needed: the signal strength from each beacon is measured at each position first and is kept in a table. When a node wants to know the position, it requests the central computer look up the table and find the position with the closest signal strength behavior to the currently sampled signal strength. Another approach uses *Radio Propagation Model*. It simulates the effect of wall, and behavior of radio signal using Rayleigh fading model, Rician distribution model, floor attenuation factor, and wall attenuation factor. Signal strength from each beacon can be estimated using this model at each position. Then like Empirical Method, the position whose signal strength behavior is closest to that of sampled value can be found. In any case whether Empirical Method is used or Radio Propagation Model is used, full information about signal behavior in the room is kept, or calculated. This requires pre-processing for each room. And the change of room geography requires change in the table or modeling.

# 3 Design and Implementation

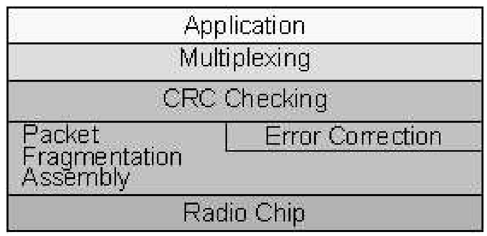


Figure 1: Network stack of DOT3 wireless sensors

The communication of wireless sensors is provided by a group of program modules called network stack. Figure 1 shows the network stack used in DOT3 wireless sensors. At the top level, an application sends and receives data in a fixed-size packet. Then, the packet is fragmented to bytes in the media access control (MAC) layer which is implemented as `ChannelMonC` module. At the sender side, MAC layer prefixes a special sequence of bytes called preamble to the data bytes so that the receiver side detects the beginning of a packet out of byte streams. At the receiver side, the radio chip forwards every data byte it receives to the MAC layer. If a sequence of bytes matches preamble, the MAC layer reads the fixed size of bytes and reassembles a packet. The received packet can be processed further in upper layers. For example, a packet can be checked of its correctness using CRC (`RFCommC` module). The network stack can use forward error correction (FEC) to correct packet errors on transit. In this case, the data bytes are encoded after being fragmented at the sender side and the received bytes are decoded at the receiver side.

## 3.1 Reading radio signal strength

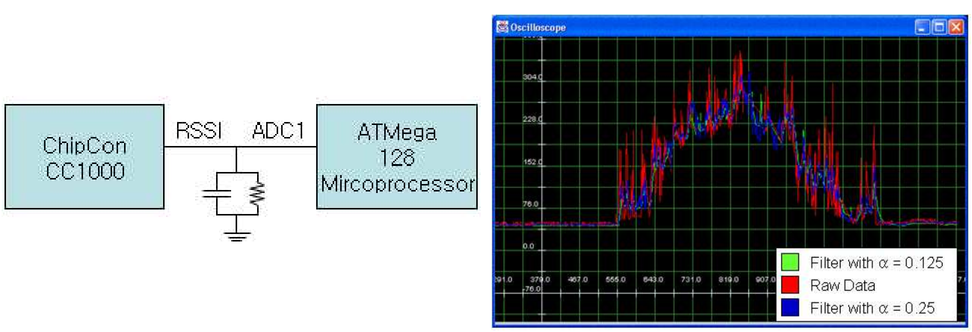


Figure 2: (a) RSSI interface to microcontroller, (b) Using exponential moving average

ChipCon radio generates an analog signal as an indication of how strong the received signal was. This RSSI (Received Signal Strength Indicator) signal has range of 0 to 1.2V (0V for the strongest and 1.2V for the weakest) and can be read using an analog digital converter. In DOT3 motes, the RSSI pin of ChipCon radio is connected to the ADC1 pin of ATMega 128 microcontroller (Figure 2(a)). Since ATMega 128 operates at VDD 3V and samples an analog signal using 10 bits, the signal strength reading can be in the range of 0 to 400.

Although the RSSI signal can be read any time, it's meaningful when the reading is associated with received packets. We read RSSI signal in the following order:

1. ADC sampling is posted when MAC layer finished receiving the preamble of a packet.

2. When ADC reading is available, it is stored in a temporary variable.

3. The MAC layer reports the signal strength with the packet when it has received all the data bytes of packet. The signal strength can be accessed through `strength` field of the packet (Figure 3(a)).

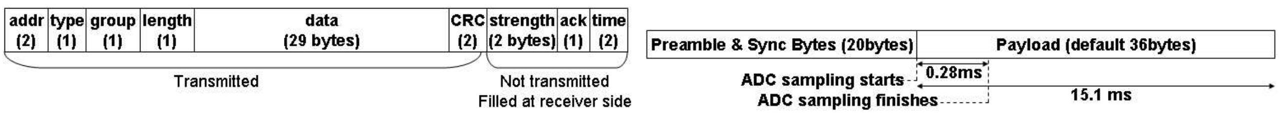


Figure 3: (a) Packet format, (b) Timing diagram of RSSI signal strength sampling

One concern is that ADC sampling may take longer than receiving a packet. We can show that RSSI signal can be sampled within packet receiving time as in Figure 3(b):

**ADC sample time**
It takes minimum 70 us and maximum 280 us (= 0.28 ms) for ADC to convert RSSI signal.

**Packet transmission time**
ChipCon radio chip transmits data at 19 Kbps with Manchester encoding.
Then, the time to receive a byte is 421 us/byte (= $\frac{8bit/bytes}{19Kbps}$).
And the time to receive a whole packet (36 bytes) is 15156 us/packet = 15.1 ms / packets (= 421 us/byte $\times$ 36 bytes/packets).

Thus, we can see that the signal strength reading can be read before the end of a packet.

We decided to filter the sampled signal strength value because the signal strength fluctuates and is not stable enough to be used as it is. We used the exponential moving average of the following formula: $Estimate = (1-\alpha) \cdot Estimate + \alpha \cdot Sampled$. If $\alpha$ is large, the signal strength estimate adjusts to the change quickly and if $\alpha$ is small, the signal strength estimate changes smoothly. For efficient implementation, simple numbers that can be calculated using bit shift operations are preferable for $\alpha$. We found that $\alpha = \frac{1}{8} = 0.125$ works reasonably well. This is shown in Figure 2(b).

## 3.2 Localization using signal strength

We can make a system that localizes sensor nodes using the signal strength. Our goal is not to tell the exact location, but rather to associate a sensor node with the nearest landmark. A group of sensor nodes that work as landmarks are placed in fixed locations. We call these nodes networks nodes. The network nodes beacon messages to show their existence. Then, other group of sensor nodes (application nodes) can hear the beacon messages from the network nodes and determine the closest network node among them. Application nodes can move around and closest network node can change. We use two algorithms to find the closest network node for an application node.

### 3.2.1 Strongest Beacon

In this method, an application node keeps a table of network nodes it has heard with the associated signal strength. Then, the application node chooses the network node with the strongest signal strength value.

### 3.2.2 Using neighboring nodes

An application node can hear beacon messages at the similar level of signal strength. Since the signal strength can be affected not just by the distance but also by the geographical reasons, we cannot necessarily say that the network node with the strongest signal strength reading is the closest one. In this case an application node can use its neighboring application nodes to break a tie.

**Neighboring application node table:** An application node $A_1$ maintains a table of neighboring application nodes whenever it overhears the membership report of the neighbors. The table has the following entries: $(ID_{app}, ID_{net}, strength)$.
$ID_{app}$ is the ID of the application node $A_1$ overheard.
$ID_{net}$ is the closest network node for node $ID_{app}$.
$strength$ is the signal strength when $A_1$ heard $ID_{app}$.

**Breaking a tie of network nodes:** When the strongest network node which $A_1$ has heard is stronger than other network nodes only within a threshold value, $A_1$ looks up the table of neighboring application nodes and finds the application node with the strongest signal value. Then, $A_1$ reports the network node $ID_{net}$ as its closest network node.

## 3.3 Test Tools

Since signal strength and the membership report messages change dynamically, we needed a tool that can help us to see the whole picture of all the sensor nodes for monitoring and debugging purposes. We developed a java application that displays the status of sensor nodes as well as logs the membership reports in database.

# 4 Experiments and Evaluation

We performed experiments in open indoor space and office environment. This is to see the radio signal strength behavior inside the building.

## 4.1 Setup

Before we use the radio signal strength as a measure of location, we did preliminary tests to see the manufacturing deviation of signal strength. In the first test, we used the same beaconing sensor node and tried all other sensor nodes as a listener node with the same condition (distance from the beaconing node and hardware settings like supply voltage and antenna). In the second test, we used one listening node and tried all other nodes as a beaconing node. As Table 1 shows, many of the sensor nodes have close characteristics. But some of them are different from others by up to 20%. To minimize the effects of manufacturing deviation, we chose motes with much variation. This hardware variation is in part caused by manufacturing process: DOT3s are manufactured manually and the length and the direction of antenna varies a little amongst sensor nodes. We expect that the hardware deviation can be reduced by calibrating the sensor nodes at manufacturing time.

Table 1: Signal strength of each sensor node

| Mote Number | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| As Sender | 49 | 49 | 49 | 56 | 49 | 49 | 49 | 49 | 49 | 55 | 49 | 48 | 50 | 49 | 49 | 49 | 49 | 49 | 49 | 49 |
| As Listener | N/A | 44 | 48 | 48 | 48 | 43 | 43 | 44 | 48 | 46 | Broken | 41 | 48 | 44 | 44 | 40 | 48 | 44 | 44 | 48 |

## 4.2 Indoor Behavior of Signal Strength

At first, we performed an experiment using one network node and one application node. In this test, we put network node at one end of the corridor, and moved the application node along the corridor as it is shown in

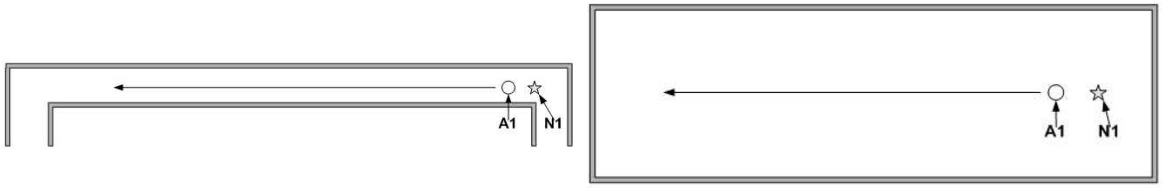


Figure 4: Experiment using one network node. (a) corridor, (b) large room

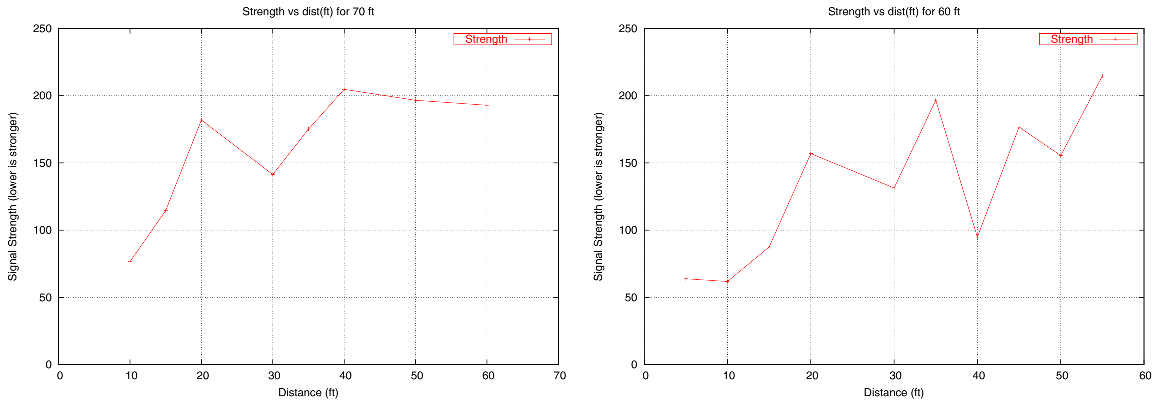


Figure 5: Results using one network node. (a) corridor, (b) large room

Figure 4(a). The width of corridor is 6ft. We recorded 100 signal strength readings at each spot. The result is shown in Figure 5(a). Smaller value means stronger signal. Signal strength was not strongly correlated with the distance. At 30ft, we can see that the signal strength got stronger even though the distance has increased. Radio signal is propagated through waves and the radio waves from the sender can take different paths while they travel and their phase can change when they reflect on some obstacles. If waves of different phase meet, then the resulting signal can be weaker. This phenomenon is called Rayleigh fading and illustrated in Figure 6.

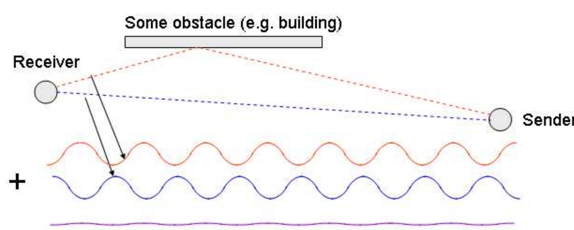


Figure 6: Rayleigh fading effect

Next, we did same test in large room and the size of room is 23 ft by 73 ft. The Network node and the application node are located as shown in Figure 4(b). The result is shown in Figure 5(b). We expected the signal strength to be more correlated with the distance. However, more radio signal interference was produced because radio waves have more chance to take different paths and produce Rayleigh fading effect. In turn, it leads to worse behavior of radio wave with more dead spots.

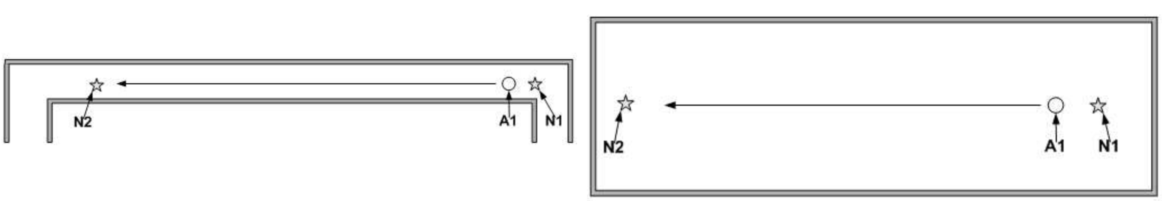


Figure 7: Experiment using two network nodes. (a) corridor, (b) large room

Then, we experimented with two network nodes. In the first test, we used the same corridor as in the

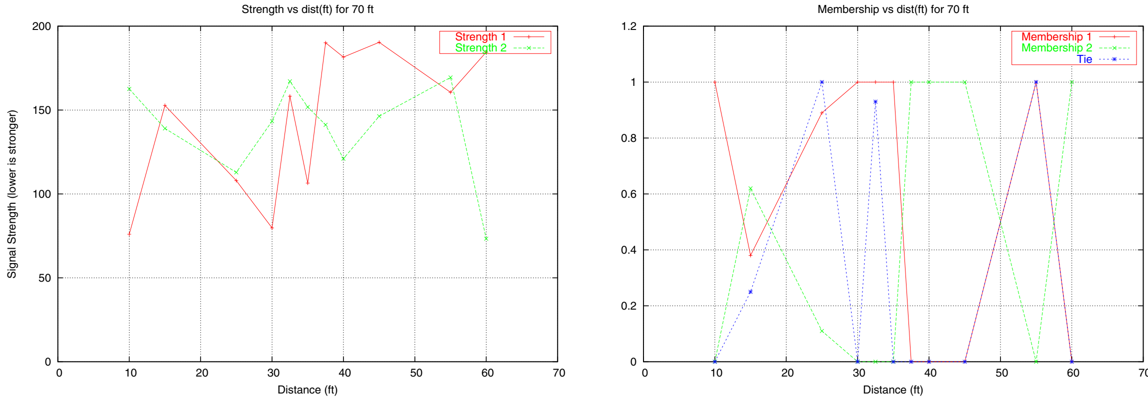


Figure 8: Results using two network nodes 70 ft apart. (a) signal strength, (b) membership

previous experiment. This time, two nodes were located at each end of corridor 70ft apart as shown in Figure 7(a). As we move the application node from one end to another end, we measured signal strengths from two network nodes with 100 readings at each position. We also recorded whether the tie occurred and which network node the membership report belongs to. Figure 8(a) shows signal strength from two network nodes. Figure 8(b) shows the ratio of membership report for each network node and the ratio of tie occurred. Rayleigh fading effect occurs here, too. The membership report is dominated by the closer network node at each end of the corridor but fluctuated in the middle.

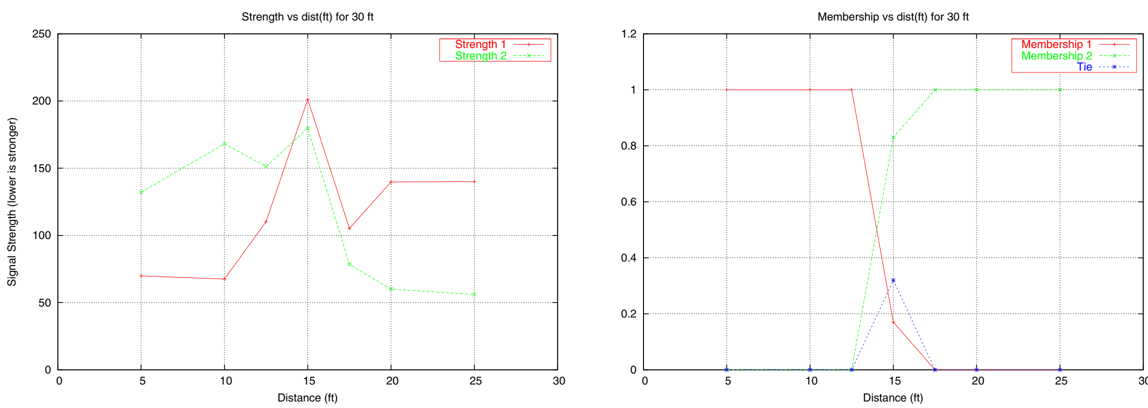


Figure 9: Results using two network nodes 30 ft apart. (a) signal strength, (b) membership

Figure 9 shows the same test with different distance (30ft) between two network nodes. Here, since the signal strength changes more drastically than before (70ft), the Rayleigh fading effect has relatively smaller influence upon signal strength. The signal strength and the membership report is close to ideal case. Tie ratio gets higher as a node moves closer to the middle because the signal strengths from two network nodes get closer.

We also did the same test in room environment as shown in Figure 7(b). Network nodes are 60ft apart. Figure 10 shows the result. As in the previous experiment with one network node, wider room environment was more affected by Rayleigh fading effect.

Then, we added more application nodes to wee whether using neighboring nodes helps correctly determining the closest network node in case of a tie. We did the test in room environment shown in Figure 11. One application node is located 10 ft apart from one network node. And another application node is located 10 ft apart from the other network node. At each location, we collected 100 readings. Figure 12 shows the results. These figures are not very different from previous ones.

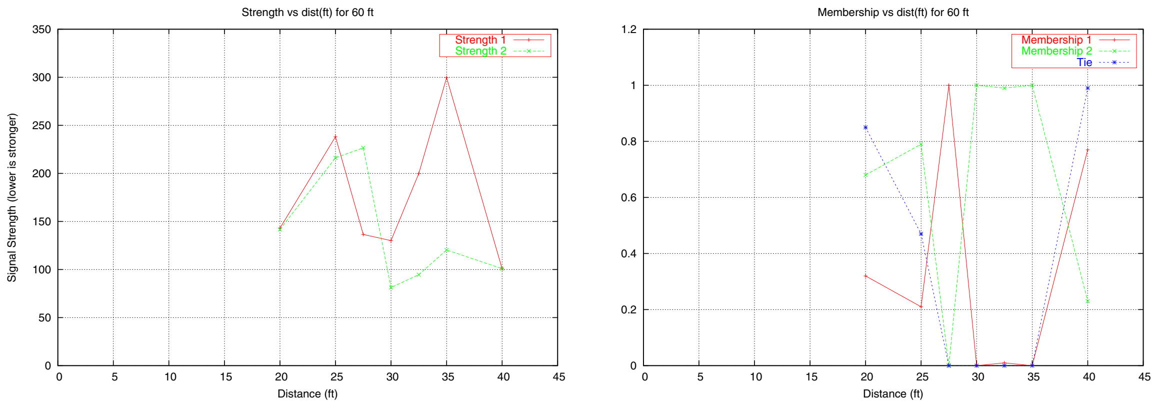


Figure 10: Results using two network nodes in a large room. (a) signal strength, (b) membership


Figure 11: Experiment using additional application nodes.

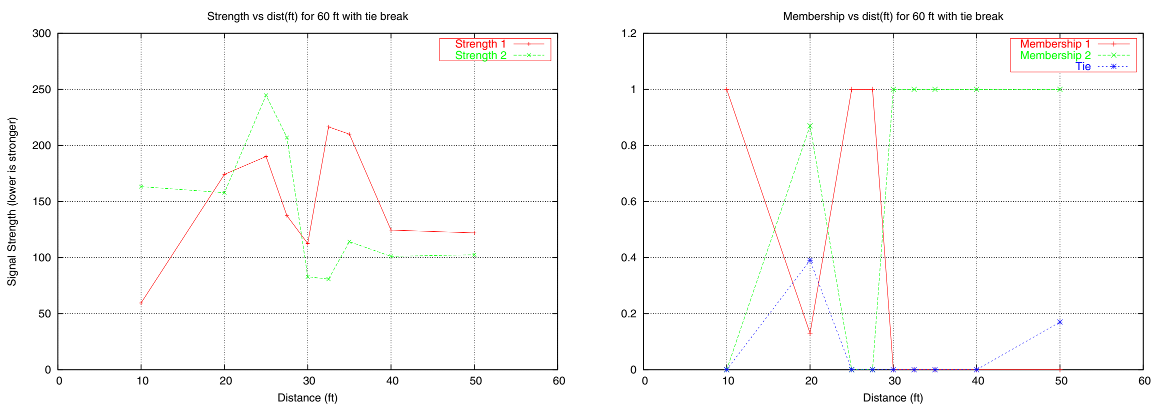


Figure 12: Results using additional application nodes. (a) signal strength, (b) membership

## 4.3 In real office environment

So far, we saw radio signal behavior in open indoor space. It showed considerable Rayleigh fading effect, and interference caused by objects. As a result, the membership report also showed somewhat queer behavior. Fortunately, however, real office environment is not as harsh as test environment in the previous section. Rooms are separated by walls, and even inside of room screens divide the room. When radio signal penetrates into the other area, even if it reaches there, its strength gets attenuated.

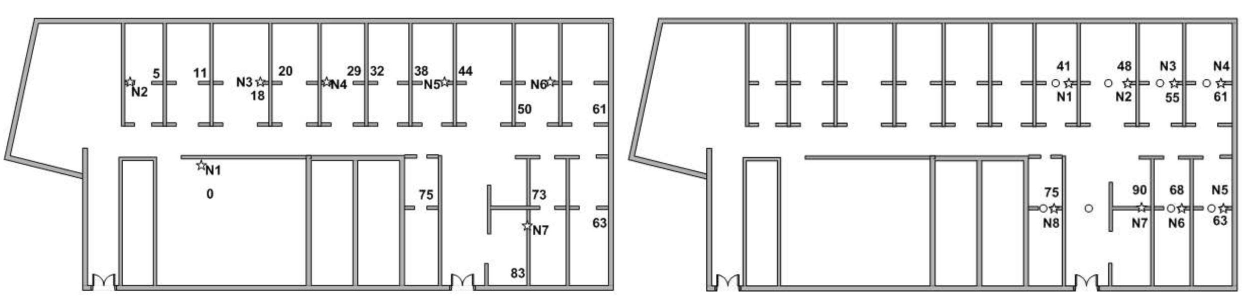


Figure 13: Experiment in office environment. (a) sparse, (b) dense

In the first test which shows the effect of the screen to the signal strength behavior, we placed network nodes at least 2 cubicles apart (one cubicle is about 10 ft) without using neighboring application nodes. Figure 13(a) shows the floor plan of the room in which the test is performed. This room is divided by screen into many cubicles and the number in the figure indicates the desk number at that position. We tested only in cubicles where a network node is located, and inside each cubicle, application node is located at the desk with desk number given. Star mark indicates network node. We collected 50 data in each spot indicated by desk number.

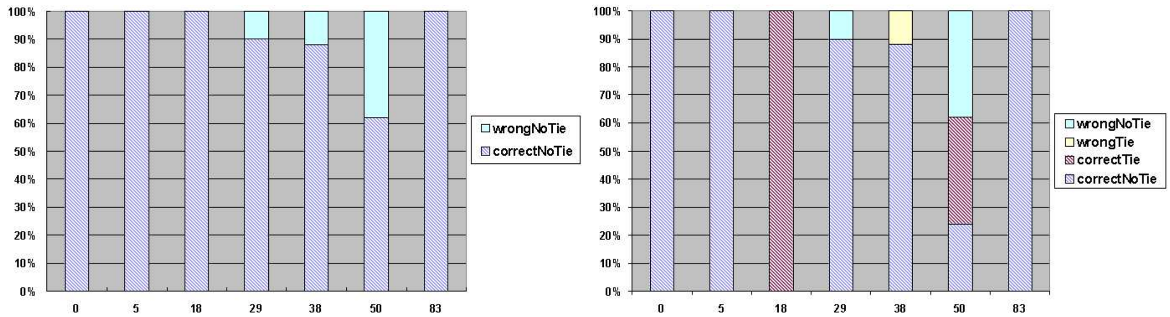


Figure 14: The percentage of correct membership reports (sparse). (a) Ratio of correct membership reports, (b) Also indicating the cases of tie

Figure 14(a) shows the results in each position. It shows the rate of correct membership reports and incorrect membership reports. In Figure 14(b), the result is further categorized depending on whether the difference of two strongest signal strengths is smaller than the threshold of 16. If we had used the tie breaker, then these cases would rely on tie breaker, showing different result. In most cases, signal strength indicates correct location without a tie.

In the next test, we placed network nodes in more densely an we also placed other application nodes. This environment setting accommodates more characteristics of real environment. Figure 13(b) shows the location of network nodes and application nodes. Star mark represents network node as before. But, desk number represents application nodes nodes for tie break in that cubicle. This time, circle indicates the location where target application node is tested in each cubicle. We collected 50 data in each cubicle.

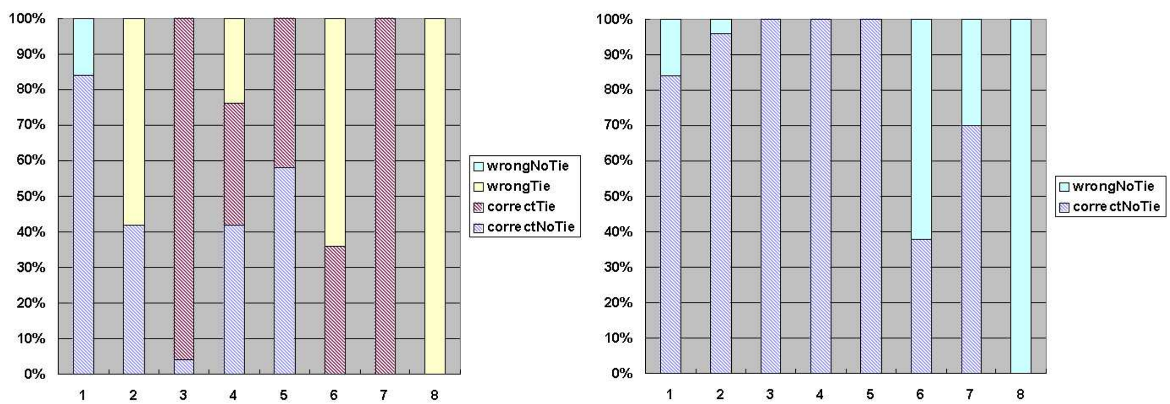


Figure 15: The percentage of correct membership reports (dense). (a) Using neighboring nodes, (b) Simulation data in case of not using tie breaker

Overall, results in this setting is worse that that of previous setting. Because the density of network is higher, application nodes hear stronger signal from network nodes in other cubicle than in the previous case. Figure 15(a) shows result with threshold 16. And Figure 15(b) shows what would happened if we didn't use tie breaker. The graph shows that using tie breaker decreases accuracy a little bit.

To see an extreme case, we tested with threshold value 64. Figure 16(a) shows the result. The accuracy

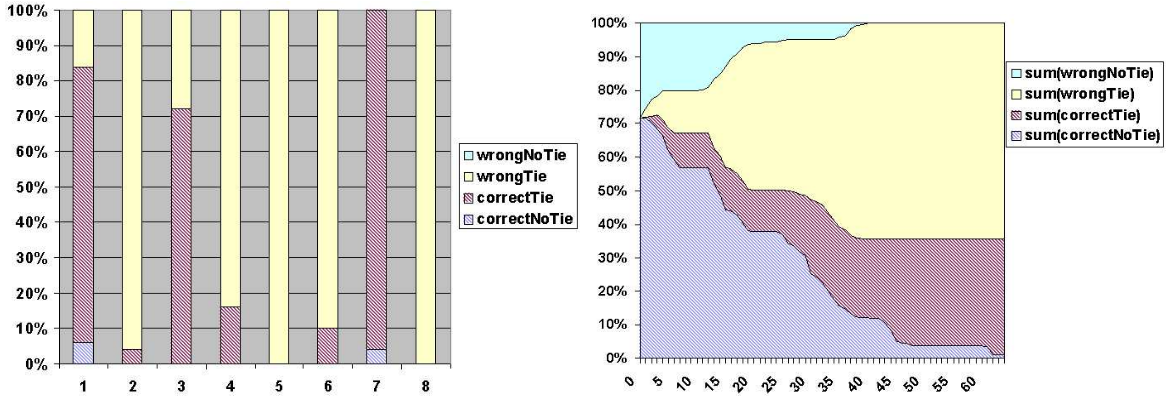


Figure 16: Test with threshold value 64. (a) Membership, (b) Simulation for other threshold values

drops further. Figure 16(b) is the simulation results showing what accuracy we can get if we used different threshold values for this test. Actually, if we test with those threshold values, their results may not exactly correspond to the simulated results. The threshold value of target node can influence other applications nodes. However, this simulation still illustrates the trend. When threshold is 0 (no tie break), accuracy is above 70%, but as threshold gets larger, accuracy drops. And finally the accuracy falls below 40%.

### 4.4 Evaluation

From the tests in previous subsections, we can observe the followings:

**The relation of signal strength to the distance** The received signal strength drops sharply up to the knee (around 20 feet), and then it drops slowly and oscillates a little. Figure 17 shows this trend. An application separated more than the knee from each network node hears the signal strength at the similar level and the membership is not dominated by any network node. This explains why one network node didn't dominate in signal strength in the middle position of Figure 8 and 10.

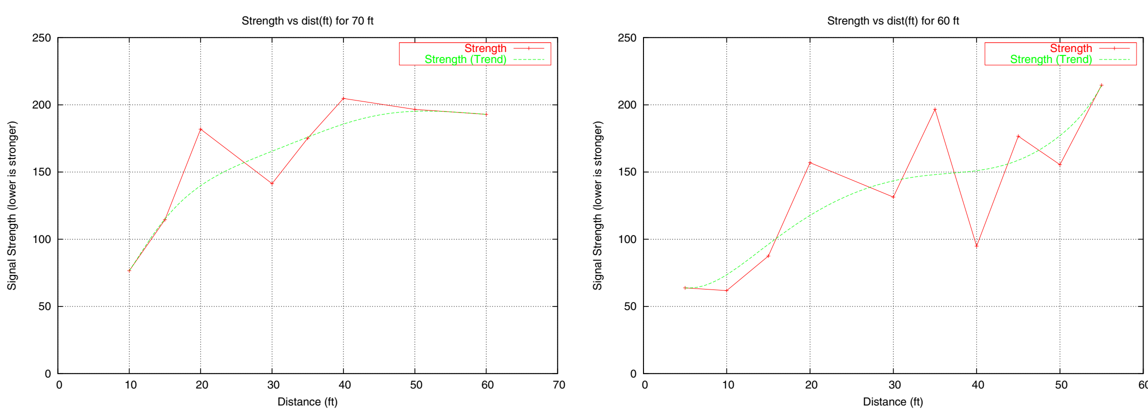


Figure 17: Trends of signal strength (a) corridor, (b) large room

**Geographical Effects** The received signal strength was affected not just by the distance from the network nodes but also by the geography like walls and screens. Figure 18 shows this example. For example, both location 18 and 50 are within 20 ft boundary from multiple network nodes. However, the rate of correctly choosing membership is much higher at 18 (100 % vs. 62 %). At location 18, network node N1 is blocked from the application node by high wall. Whereas at location 50, network node N7 is on top of screen and can reach the application node with line of sight. We also found that the signal strength indicated geographical proximity in most cases, but there were exceptions like the location 8 in Figure 15(a).

**Using neighbors for tie breaking** Using the signal strength of neighbor nodes didn't help when the

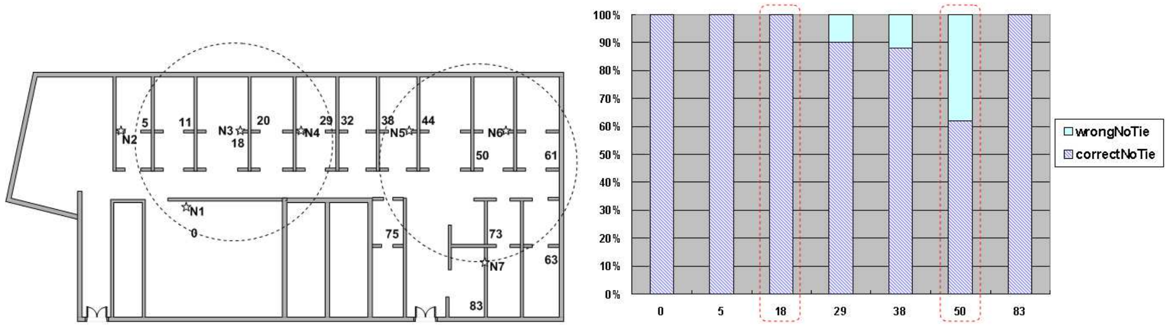


Figure 18: Geographical effects on signal strength

difference of received signal strength of network nodes is not large. This is because the neighboring application nodes can hear the signal strength at the similar level and cannot help breaking the tie.

## 5 Conclusion

ChipCon radio generates signal strength when it receives data and we used this signal strength as a way of localizing sensor nodes. Compared to [1] and [2] we didn't use any special hardware (ultrasonic transceiver) and preprocessed location-specific data.

Our experiments showed that the signal strength drops sharply up to the knee (around 20 feet) and starts to drop slowly afterwards. Up to this point, signal strength indicated distance well, and was useful for membership determination. However, signal strength was not clearly correlated to the distance after that point. Experiments in real office environment showed that the signal strength depends on geography as much as the distance. Breaking a tie using neighboring application nodes didn't help reducing the incorrect membership reports because the neighboring nodes can have a tie.

In conclusion, using the signal strength of ChipCon radio is not an accurate measure of location, However, it can be effective when network nodes are separated more than the knee (around 20ft) and application nodes are within the knee from any of network nodes. Moreover, this method can be easily deployed because it doesn't need additional hardware nor preprocessing.

## Acknowledgements

This work is funded in part by the DARPA NEST Contract F33615-01-C-1815.

## References

[1] N. B. Priyantha, A. Chakraborty, and H. Balakrishnan, "The Cricket location-support system," *MobiCom,* 2000

[2] P. Bahl and V.N. Padmanabhan, "RADAR: An in-building RFbased user location and tracking system," *Procedings of INFOCOM,* 2000

[3] J. Jeong and S. Kim, "Dot3 Radio Stack," *http://webs.cs.berkeley.edu/retreat-1-03/,* NEST retreat Jan. 2003

[4] "ChipCon CC1000 Data Sheet," *http://www.chipcon.com/files/CC1000_Data_Sheet_2_1.pdf*