# Design and Calibration of the SpotON Ad-Hoc Location Sensing System

Jeffrey Hightower*[1], Chris Vakili[1], Gaetano Borriello[1], and Roy Want[2]

[1] University of Washington, Computer Science and Engineering, Box 352350, Seattle, WA 98195

[2] Intel Research, 2250 Mission College, Blvd, Santa Clara, CA 95054

**Abstract.** The location of equipment, people, and other physical things is essential data to many emerging applications. Unfortunately, location data is often not easy to obtain. We have created SpotON to investigate *ad-hoc location sensing*, a flexible alternative to infrastructure-centric location systems. SpotON tags use received radio signal strength information as an inter-tag distance estimator. In this paper, we describe ad-hoc location sensing and the SpotON approach. We present specific results regarding calibration of the SpotON radios and suggest directions for further research.

## 1 Introduction

Location sensing capability is often considered a basal ingredient in the smorgasbord of necessary infrastructure for ubiquitous computing: We want our intelligent home to respond to movements of the inhabitants. We want to capture experimental activity in a biological laboratory. We want to solve once and for all the hackneyed example of routing our manuscript to the nearest printer. Unfortunately, the necessary location data is often difficult to capture using existing techniques.

We are working in a nascent research area called ad-hoc location sensing. Ad-hoc location sensing is a fusion of concepts from object location tracking and ad-hoc sensor networking. Objects are located by homogeneous sensor nodes without central control. Ad-hoc location sensing systems are quite flexible and can provide both absolute and relative location data and can support both infrastructure-centric and wearable application models.

Hoping to gather real-world information not available using simulation techniques, we have designed and built hardware that will serve as object location tags, part of a project called SpotON. SpotON tags use received radio signal strength information (RSSI) as a sensor measurement for estimating inter-tag distance. Using many collocated nodes, the measured positional accuracy can be improved through algorithmic techniques and erroneous distance measurements caused by signal attenuation (e.g. by metal objects in the area) can be automatically factored out.

* This work is supported by DARPA contract N66001-99-2- 8924, subcontract 993572. Jeffrey Hightower is supported by a Microsoft Research fellowship.

In this paper we present ad-hoc location sensing and results concerning calibration of the SpotON radios and signal strength capture circuitry. Proper calibration is an important step in any sensor system. In our context, calibration means the construction of tag specific configuration information such that each tag can transmit at the same power as the others and map its received radio signal strength measurements to an estimated distance from a transmitter. Section 2 presents relevant background information. Sections 3 and 4 discuss ad-hoc location sensing and the SpotON approach to the problem. In Section 5 we present the calibration process used by the SpotON sensor tags. Finally, we summarize our future work and offer conclusions in Sections 6 and 7.

## 2 Background

### 2.1 Location Sensing

There have been many systems and architectures over the years tackling the problem of automatically determining object locations. Since each was developed to fulfill a different goal, they vary widely in many parameters including accuracy, cost, size, configurability, security, and reliability. Examples include the Global Positioning System (GPS) [12], Active Badges and the Xerox ParcTAB [21] [22], AT&T Cambridge Ultrasonic Bats [8] [9], Microsoft Research's RADAR [1], the Smart Floor from Georgia Tech [18], PinpointCo's radio tags [4], Cricket from MIT [19], and various computer vision systems [5] [15]. There is also a large body of work in location tracking for virtual reality and motion capture for computer animation [2].

### 2.2 Ad-Hoc Sensor Networking

Ad-hoc sensor networking has a large community investigating many issues from distributed computation to cryptography to ad-hoc routing protocols to data dissemination in low power wireless networks [13]. A primary driver for this work is the DARPA SensIT program which seeks to create "cheap, pervasive platforms that combine multiple sensor types, embedded processors, positioning ability and wireless communication." [17]

## 3 Ad-Hoc Location Sensing

Recently we have seen a fusing of ideas from object location tracking and the large body of work in ad-hoc networking. The result is the new area of research we call ad-hoc location sensing. The defining characteristics of this area are:

1. ***Location*** - Relative and absolute locations of physical objects as well as past and predicted locations are the basic quantities of interest. In addition to precise (X,Y,Z) *positions* such as those provided by GPS, *location* encompasses rough or abstract ideas of where something is: in the bedroom by the window, in Denver, near Dr. Nancy Jones, next to an automated teller machine, on the #71 metro bus approaching Union Station.

2. ***Homogeneity*** - As in much ad-hoc networking research, nodes in the system are functionally homogeneous. Those nodes with distinguishing characteristics such as fixed locations or additional capabilities are the exception and, although they may provide valuable additional information, they are not mandatory for system operation. In particular, an ad-hoc location sensor network does not require fixed or distinguished basestations observing and directing.
3. ***Socialistic Information*** - In general, more information about the whole cluster can be gleaned as the participating sensor node count increases. Algorithms can treat nodes as equal partners in storing and disseminating information. Applications or agents interested in leveraging the cluster behavior can be attached to any node and are not forced to interact through a global intermediary. Mobile and wearable as well as traditional infrastructure-centric application models are supported.

Research into ad-hoc networking to date, which includes routing protocols and location sensing, has mainly been carried out through simulation. For example, [6] presents an approach to location determination using a radial model of inter-node radio connectivity evaluated with a multi-node simulation. Although simulation is a powerful and useful tool, the unpredictable nature of indoor radio signal propagation along with our desire to discover issues in deploying real-world applications has motivated us to develop a fully realized solution. We feel that real hardware experiments will lead us to defensible conclusions concerning the feasibility of using signal strength for ad-hoc location sensing. Colleagues at Berkeley [14] and USC-ISI [3] are investigating related issues using their own hardware platforms and compatible radio technology.

## 4 The SpotON Approach

We have created the SpotON hardware tags to study ad-hoc location sensing and evaluate the use of received radio signal strength information (RSSI) as a measurement tool. The choice of measurement technology was motivated by our target scenario: flexible or temporary sensor deployments in small scale environments such as offices with floor space less than $16m^2$. For example, a strategy room can be temporarily "SpotON enabled" simply by attaching one or more tags to the walls and interior. Tagged people and objects inside the room can then be located relative to one another (or absolutely if the fixed tags are configured to know their absolute location). Both infrastructural and wearable applications in the room can leverage the location data.

### 4.1 High Level Operation

We will now briefly describe the high level operation of the SpotON hardware as nodes in an ad-hoc location sensing network.

**Fig. 1.** A SpotON Ad-Hoc Location Sensing Tag

1. A SpotON tag is attached to things we wish to localize. Figure 1 shows a photograph of a SpotON location sensing tag. Note that this is an experimental prototype and could be shrunk dramatically, even with today's technology. Under normal conditions, a tag can operate for approximately 30 hours on 2 AA batteries. Operating time could be dramatically extended to days or weeks using advanced mobile battery technology such as that found in PDAs and cellular telephones.
2. Tags beacon radio packets of a calibrated power at randomized intervals. The randomization, along with a simple listen and back-off technique allows clusters of tags to use the shared 916.5MHz radio spectrum efficiently. An alternative approach is to beacon periodically with random phase difference back-off relative to other beacons. This approach will converge to a tag-specific beacon time slot. In both cases, packet collisions are reduced and the attempt is made to maximize fairness and aggregated throughput.
3. Any tags hearing a radio beacon measure the received signal strength information (RSSI) subject to their receiver specific calibration model. RSSI is used to estimate the distance from a transmitter.
4. Beacon packets may also contain a measurement history payload. This payload distributes measurements around the cluster allowing any node to quickly aggregate a global snapshot needed to perform location calculations. Both infrastructure-centric and wearable application models are supported. For example, emulation of infrastructure-centric location systems can be achieved by simply attaching an application server to one of the fixed nodes. Wearable applications attached to a tag can participate however they wish using the measurement information available to all cluster participants.

### 4.2 Why Radio Signal Strength?

Any sensor technology meeting the homogeneity and socialistic information goals of Section 3 and providing distance estimates between two arbitrarily placed nodes may be suitable for our ad-hoc location sensing research. Given our target scenario, we believe applying received radio signal strength information to the problem is reasonable.

Infrared and ultrasound sensors are usually directional and thus do not readily facilitate measurements between arbitrarily placed nodes. Other solutions in the RF domain such as angle of arrival (AOA) or signal time of flight (as in radar and GPS) can be used for location sensing but at potentially high monetary and power cost in the small scale. GPS-like approaches usually require precisely installed basestations and more centralized control; information is not socialistic nor are sensor nodes homogeneous.

The SpotON radio signal strength measurement is cost and power effective [11]. SpotON tags require no complex digital signal processing hardware. All SpotON radio components are off the shelf parts around a general purpose microcontroller. The SpotON radio architecture uses the RFMonolithics TR1000 916MHz radio transceiver and the MC68EZ328 "Dragonball" processor.

### 4.3 Hardware Design

SpotON tags are actually robust location sensing platforms containing other sensors such as accelerometers and infrared detectors, however, only the radio and signal strength capture subsystems are pertinent to this paper. Refer to [11] [10] for a design history and schematic listing of the SpotON hardware. Care has been taken to assure precise and repeatable RSSI measurements and adjustable transmit power. Figure 2 shows the radio architecture we use to achieve this goal.

**Transmit Power Adjustment.** SpotON tags have hardware adjustable transmit power via a percentage attenuation factor (e.g. an attenuation setting of 35 implies transmissions of roughly 35% maximum output). By placing a 100-tap digital potentiometer and series resistor on the transmit modulation pin (TX-MOD) of the TR1000 radio transceiver chip, we can adjust the amount of current into the pin and hence the overall output power of the transmitter. Results showing the success and usefulness of this approach will be presented in later sections.

**Signal Strength Recovery.** It is possible to recover received signal strength information (RSSI) from the baseband output of the TR1000. The baseband pin modulation rides on a variable DC level of approximately 1.1V. A decrease in RSSI causes the baseband modulation peak-to-peak amplitude to decrease from a maximum of 685mV by approximately 10mV/dBm [16]. Figure 3 illustrates a measurement of this change using a simple peak voltage measuring circuit

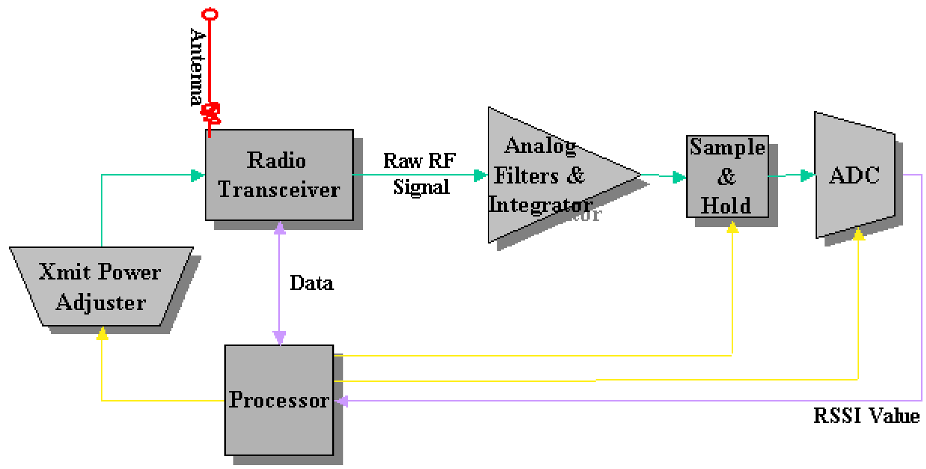


**Fig. 2.** SpotON Radio Architecture

connected to the baseband pin. Bear in mind that this graph naturally reflects a change of half the predicted decrease (5mV/dBm) since we are measuring peak voltages of an alternating signal centered around 1.1V DC.

Given the drifting baseband DC level and the fact that *peak-to-peak* voltage is the important quantity indicating RSSI, SpotON tags need to condition the signal before taking a voltage measurement. The baseband signal is first AC coupled down to a DC reference level. The signal is then rectified and sent through a negative gain amplifier (-5.6x gain). The amplifier output is then peak detected by a low pass filter with a software clearable storage capacitor. Finally, the resulting charge is compared to the DC reference level using a 10-bit differential analog to digital converter (ADC). The integer reported by the ADC is the RSSI value handled by the SpotON tag software. Refer to the SpotON schematics for the circuit diagram [10].

## 5 Calibration

As in any sensor system, calibration is important to the SpotON ad-hoc location tags. By calibration we mean the creation of tag specific information such that any given tag can transmit at the same power as the others and can accurately map its RSSI measurements to an estimated distance from a transmitter. Characterizing and accounting for tag-specific variations in this way insulates higher level ad-hoc location algorithms from hardware dependencies and the details of RSSI processing.

We begin by presenting a distance dependent RSSI prediction function in Section 5.1. Section 5.2 then demonstrates how and why real measurements can deviate from the prediction. Specifically, we present experimental data showing

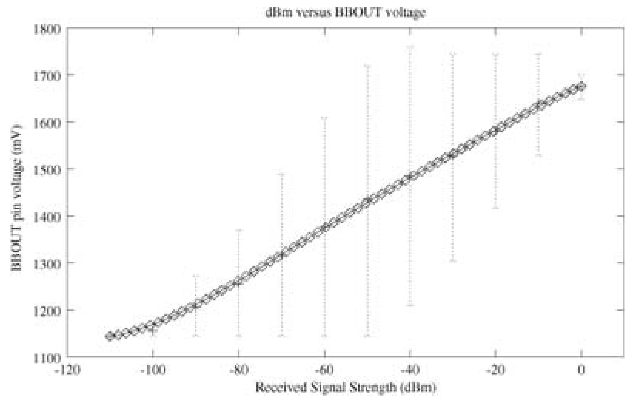


**Fig. 3.** Received signal strength versus baseband pin voltage using a simple peak voltage detector [16]. Error bars are from data provided by the manufacturer.

that SpotON sensors may measure RSSI differently at a given distance. We identify where variability occurs (e.g. receive versus transmit) and what can be done to reduce each type of error. Finally, the implementation of a semi-automatic calibration process for the SpotON ad-hoc location sensors is presented in Section 5.3.

### 5.1 Predicting Behavior

Using the distance dependent indoor path loss model of Seidel and Rappaport [20], we can construct a formal SpotON RSSI prediction function based on the parameters of the SpotON hardware. Equation 1 shows this prediction. $RSSI_{max}$ is the value reported by the ADC under a full power 685mV peak-to-peak baseband swing. $\Delta ADC/dBm$ is the difference reported by the ADC when RSSI changes by 1dBm (10mV reduction or gain in baseband peak-to-peak). The path loss exponent $n \approx 2$ varies depending on the transmit source power, the receiver hardware, and the radio characteristics of the environment. It captures the rate at which path loss increases with distance.

$$RSSI_{pred}(d) = RSSI_{max}(d_0) - \frac{\Delta ADC}{dBm} * n * 10 \log_{10}(\frac{d}{d_0}) \tag{1}$$

In the current SpotON hardware design, $RSSI_{max} \approx 778$ and $\Delta ADC/dBm = 11.4688$. Given an estimate for $n$ and assuming a full power measurement occurs when transmitter and receiver are at an extremely close reference distance $d_0 = 1cm$, we can predict $RSSI_{pred}$ for any centimeter distance $d$ from the transmitter. Figure 4 shows the prediction curve for $n = 1.7$ and $n = 2.5$. To show prediction tenability, we include a scatter plot of real RSSI measurements taken in the indoor office environment by a single transmitter-receiver pair using 31% and 49% transmitter attenuation.

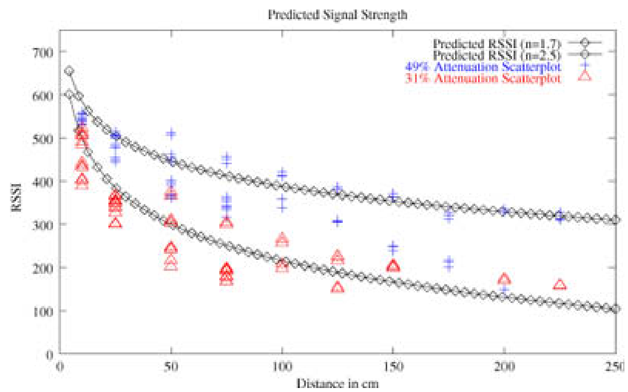


**Fig. 4.** Predicted RSSI based on the hardware parameters using path loss exponents $n = 1.7$ and $n = 2.5$. The scatter plot shows real RSSI measurements of a transmitter-receiver pair using 31% and 49% attenuation.

Even in this preliminary plot, we notice an apparent dependence on transmit power as well as the existence of measurement noise. We also observe that adjusting $n$ may more accurately approximate receive response. The next section will examine these observations in greater depth.

### 5.2 Identifying Variability

In this section we show why real RSSI measurements may deviate from the prediction by testing the hypothesis that SpotON sensors measure RSSI differently at a given distance due to inherent hardware variations. We identify where error is introduced and suggest mechanisms needed to mitigate each type of error.

**Data Collection.** Figure 5 shows the experimental setup used to gather the RSSI measurement data used in our analysis. The experiment was carried out as follows:

1. Select an arbitrary tag to be the transmitter and place several other tags at a fixed distance in the two-dimensional plane from the transmitter.
2. Trigger a test cycle on the transmitter consisting of a sequence of repeated packets at increasing transmit powers. Each receiver measures RSSI and stores the values in its on-board memory. Stored measurements from this cycle are downloaded from all receivers to a laptop running data logging software.
3. Repeat the test cycle process until each tag has had a chance to be the transmitter. This repetition captures all permutations of transmit and receive for the set of tags under test.
4. Increase the distance by a known amount and repeat.

**Fig. 5.** Experimental setup for the distance cycle experiment

**Transmitter Variations.** Transmitters set to the same attenuation percentage may have slightly different output power. We corroborate this assertion in this section. Figure 6 shows graphically that an attenuation percentage of 50% actually results in slightly different transmit power measured by receiver #5. Although not shown, results are correspondingly similar for other receivers. The curves are a nonlinear least-squares fit to the equation $R = a - 11.4688 * b * 10\log_{10}(d)$ where $R$ is RSSI, $d$ is the inter-tag distance, and $a, b$ are the fit variables. This equation is a simplified form of the physical model presented previously in Equation 1. This simplified form is sufficient in this context.

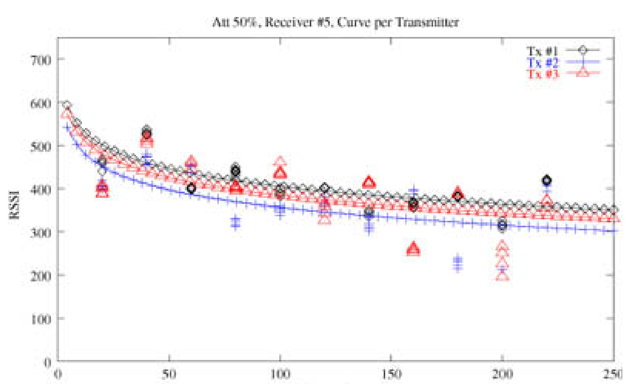


**Fig. 6.** The response of receiver #5 to 50% transmit attenuation from 3 transmitters. Demonstrates transmitter hardware variability across different tags.

We can now prescribe a mechanism to ameliorate transmitter variability: regulation of transmitter output power on a tag-specific basis. Regulation can be accomplished by finding the attenuation percentage needed by each individual tag to match a global metric of transmitter power. The implementation of the transmitter calibration process will be presented in Section 5.3. For completeness, Figure 7 validates this approach by showing evidence that the attenuation percentage does in fact have a regular effect on transmit power.

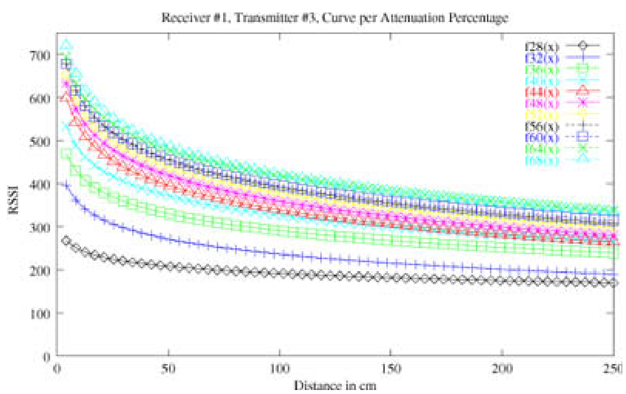


**Fig. 7.** Measurements of receiver #1 using transmitter #3 with a curve shown for several attenuation percentages. Shows that attenuation percentages are successful in regulating transmit power.

**Receiver Variations.** Receiver hardware varies more than transmitter hardware. Figure 8 shows variability across multiple receivers in response to transmitter #5 at 52% attenuation. As before, results are similar for other transmitters. Note that none of the error shown in this figure is caused by transmitter variations shown in the previous since those variations were in the context of multiple transmitters.

Unlike the attenuation percentage mechanism on the transmitter, the SpotON receiver hardware is not physically adjustable. Receiver adjustments are accomplished by parameterizing the distance to RSSI mapping (Equation 1). Receiver calibration minimizes error in distance prediction[1].

We have identified two sources of receiver variability and the calibration to help compensate for each. The first is differing values of $RSSI_{max}$ (the RSSI value reported in response to a full power transmission). Equation 2 shows the computation of $RSSI_{max}$.

---

[1] Distance prediction is, of course, Equation 1 solved for *dist* instead of $RSSI_{pred}$ but the calibration discussion here is just as valid treated in either direction.

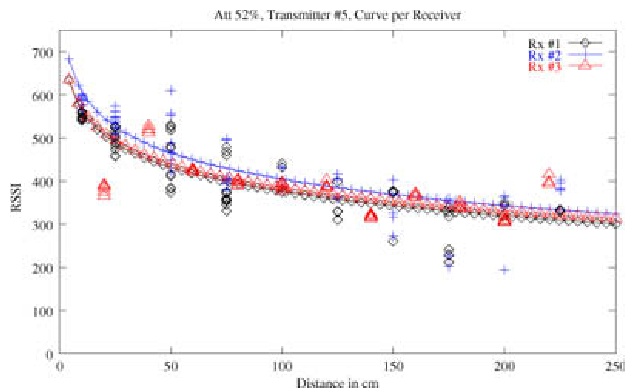


**Fig. 8.** Receiver response to transmitter #5 using attenuation percentage 52%. Shows variability in receiver response.

$$RSSI_{max}(V_{ref}) = 2^{bits_{ADC}} - \frac{V_{ref}}{V/bit} \quad (2)$$

The resolution of the ADC in bits is $bits_{ADC} = 10$. $V/bit = 0.002441406$ is the voltage change causing a 1-bit delta on the ADC. Recall that during the RSSI recovery process, the radio baseband signal is AC coupled down to a DC reference level. $V_{ref}$ is this level. $V_{ref}$ varies from tag to tag due to issues such as resistor tolerances. $V_{ref}$ can vary over the range approximately 0.5-0.7 volts resulting in a $RSSI_{max}$ range of 738-818. Fortunately, as part of calibration the ADC hardware can sample its DC reference level outside the normal RSSI measurement context. A tag specific $RSSI_{max}$ value can then be computed locally by each tag.

The second inter-tag receiver variability we identify manifests itself as a difference in the rate of RSSI decreases with increasing distance. The $n$ parameter in our RSSI-distance equation models this rate. We know that $n$ is a function of transmit power, receiver hardware variability, and physical effects caused by the environment containing the receiver and transmitter at a given moment in time. Given known transmit power, it stands to reason that adjusting $n$ to account for receiver hardware variability is the best that can be done in cleanroom calibration where no dynamic environmental effects are considered.

We have shown how SpotON sensors do in fact measure RSSI differently due to hardware variations. We found that receiver variability is slightly greater then transmitter variability and suggested ways of handling each. Transmitter calibration involves finding the attenuation percentage for each tag yielding a known output power while receiver calibration is computing $RSSI_{max}$ and adjusting $n$ to fit the prediction equation to data sampled at a known distance.

### 5.3 Calibration Implementation

This section describes the implementation of calibration on the SpotON ad-hoc location sensing tags using results from Section 5.2. The process is designed to be accurate yet simple from the perspective of the human operator directing the calibration.

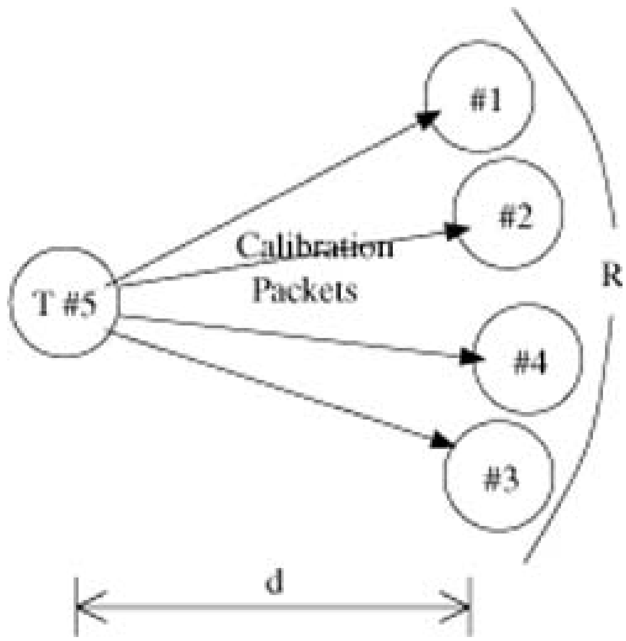


**Fig. 9.** Transmitter #5 is calibrating receivers at distance $d$.

1. Choose a transmitter $T$ and set its attenuation percentage to a reasonable default value.
2. Calibrate all receivers $R_1 \ldots R_n$ to this transmitter at a known distance. See Figure 9.
3. Choose one of these receivers $R_i$ and sequentially calibrate the rest of the transmitters relative to it. See Figure 10.

Upon completion, each tag has a unique attenuation percentage level and appropriately parameterized RSSI to distance mapping. All tags can then transmit at the same physical power level and be able to estimate transmitter to receiver distance based on their own receive characteristics. We will now fill in the pertinent details of this process.


**Fig. 10.** Receiver #1 is calibrating transmitter #3 at distance $d$.

**Calibration Order.** A baseline for calibration must be established by designating an arbitrary SpotON tag as a reference. Section 5.2 indicated that transmitters vary somewhat less than receivers across units. Realizing that objects drawn from a class exhibiting lower variability make better reference candidates, it stands to reason that we should arbitrarily choose a reference transmitter and calibrate the receivers first. After the receivers are calibrated, one can be selected to calibrate the transmitters second. The reference units themselves are calibrated last.

**Receiver Calibration Details.** Receiver calibration is the computation of a tag specific parameterization for the distance to RSSI mapping function. Receivers $R_1 \ldots R_n$ are placed at distance $d$ from the transmitter. Empirical data suggests that $d = 50cm$ is a reasonable choice because radio signals are strong yet the tags are not extremely close.

Transmitter $T$ sends a sequence of 100 calibration packets. Receivers save the RSSI for these packets in on-board memory. Missed packets are inconsequential since calibration parameters can be computed using fewer packets. Note that repeated calibration packets are sent at a rate that gives the receiver adequate time to settle on a stable RSSI reading and to reset between packets. The minimum packet length is 30ms while the maximum RSSI acquire time is 12ms from the start of the packet. The minimum inter-packet spacing is 44ms while it takes only 6ms to clear the RSSI circuitry between packets. The receiver computes its calibration by sampling the DC reference level to compute $RSSI_{max}$ and fitting the $n$ parameter using the saved RSSI calibration values. The computed $RSSI_{max}$ and $n$ values are stored in nonvolatile memory. All receivers are now calibrated except the one collocated with the reference transmitter T. This one may be calibrated after transmitter calibration using the same process but a different transmitter.

**Transmitter Calibration Details.** Transmitter calibration matches transmitter output power of all tags by using a calibrated reference receiver. The procedure is a binary search for the proper attenuation percentage directed by a previously calibrated receiver.

To setup the process, a single calibrated receiver is chosen. Only one receiver should be used so acknowledgment messages do not collide. Transmitters $T_1 \ldots T_n$ are sequentially put at distance $d$ from the reference receiver. Observe that the transmitter used in receiver calibration is already calibrated by definition. Each $T_i$ is manually triggered to send repeated packets. The reference receiver responds with one of three acknowledgment packets after comparing the measured RSSI to the RSSI predicted by its calibrated model:

- $ACK_T(\uparrow)$ - The transmitter needs to send at a higher attenuation percentage.
- $ACK_T(\downarrow)$ - The transmitter needs to send at a lower attenuation percentage.
- $ACK_T(o)$ - The transmitter is using an acceptable attenuation percentage.

Based on these responses, the transmitter is guided through a binary search for the proper attenuation percentage and stores the result in nonvolatile memory. Two failure modes in this process need addressing. First is the possibility of a packet or response getting lost. This exception is resolved by using a standard transmitter sequence number and timeout technique to trigger retransmission. The second failure mode is a boundary condition in the binary search. Should the attenuation percentage go too low during the search, the transmitter packet will never be received and the calibration process will hang. The solution here is a bootstrap procedure before beginning the binary search. Starting from attenuation percentage 0, the transmitter sends at linearly increasing attenuation percentages until receiving the first acknowledgment. Let this attenuation be called $att_{min}$. The binary search can then be performed over the range $(att_{min}, 100)$ from a starting attenuation percentage of $att_{min} + \frac{100-att_{min}}{2}$. Figure 11 shows a sample transmitter calibration sequence for tag #3.

## 6 Future Work

There are several open avenues for future work:

- ***Multiple transmit power levels and the corresponding receiver response parameters.*** We may be able to achieve a more accurate distance estimate by sampling RSSI from packets transmitted at different attenuation percentages. Higher and lower transmit power levels have the empirical effect of contracting or expanding the distance axis of the RSSI versus distance plot. Using this technique, the potential exists for increased accuracy and range although reflections and other environmental effects might hurt accuracy at higher powers in some environments. Multiple transmit powers also presents the logistical challenge of managing increased local cluster size at higher powers.

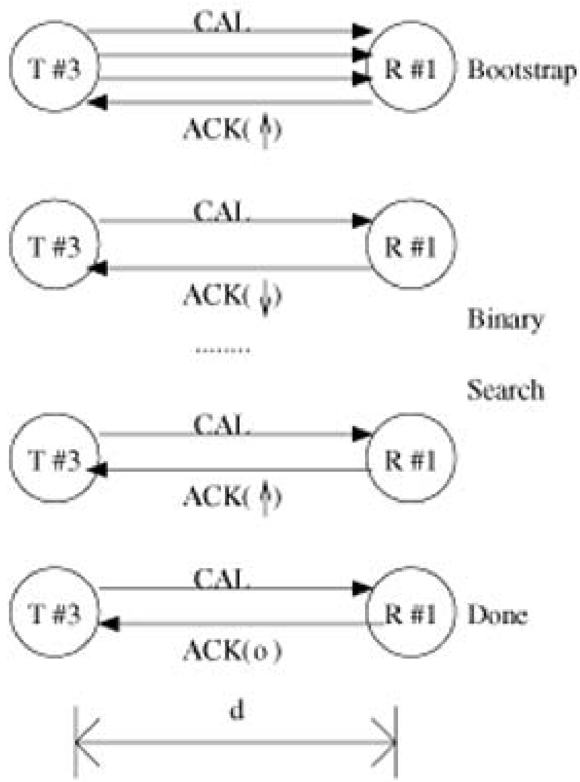


**Fig. 11.** Transmitter calibration of SpotON #3.

– ***Dynamic and ongoing calibration.*** This extension could be as simple as updating $RSSI_{max}$ periodically or as complex as varying $n$ dynamically in response to known situations in the RF environment. Another opportunity for dynamic calibration is robot assistance. Robots who know their location based on maps could be employed to assist in dynamic calibration [7]. Robot mounted tags also provide the chance to consider nodes which have well-known locations yet are mobile.
– ***Testing techniques.*** We should be able to verify a deployment of sensor tags and characterize the behavior. For example, how does the accuracy vary across different portions of an installation and where can we place additional tags for maximum enhancement. Finally, how can we best provide a visualization of system behavior in a manner that is meaningful for understanding and debugging.
– ***Other distance measurement technologies.*** Armed with a more complete understanding of the way radio energy propagates indoors, it may be reasonable to consider alternative approaches to using radio signal strength as our distance estimate. RSSI, although workable, is still somewhat unpredictable and measurement variances are sometimes higher then desirable. Perhaps a more accurate although potentially more complicated and expensive approach would be to devise a radio time-of-flight sensor. No matter which technology is chosen, it must meet the three ad-hoc location sensing criteria presented in Section 3.

## 7 Conclusion

In this paper we have presented *ad-hoc location sensing*, a combination of ideas from object localization and ad-hoc networking. An ad-hoc location system provides an intriguing alternative to location systems built with expensive fixed infrastructure and central control. Ad-hoc location systems can provide relative and absolute location data and can support both infrastructure-centric and wearable application models. We characterize ad-hoc location sensing with three qualities: *location*, *homogeneity*, and *socialistic information*.

Our approach to the problem is SpotON, a system of ad-hoc networking tags which use received radio signal strength information to estimate inter-tag distance. In particular, this paper has presented a method of calibrating SpotON radios to handle hardware variability and increase estimate accuracy. In addition, we have discussed exciting directions for future work in ad-hoc location sensing.

## 8 Acknowledgments

The work presented in this paper was performed in consultation with Marshall Bern, Köenraad Van Schuylenbergh, and Frank Vest at Xerox PARC and Sushant Jain and the Portolano research group at the University of Washington. Thanks go to all of these folks for their valuable insight and assistance.

## References


1. Paramvir Bahl and Venkata Padmanabhan. RADAR: An in-building RF-based user location and tracking system. In *Proceedings of IEEE INFOCOM*, volume 2, pages 775–784, March 2000.
2. Steven R. Bible, Michael Zyda, and Don Brutzman. Using spread-spectrum ranging techniques for position tracking in a virtual environment. In *Second IEEE Workshop on Networked Realities*, Boston, MA, October 1995.
3. Nirupama Bulusu, John Heidemann, and Deborah Estrin. GPS-less low cost outdoor localization for very small devices. *IEEE Personal Communications*, 7(5):28–34, October 2000. Special Issue on Smart Spaces and Environments.
4. PinPoint Corporation. Website, 2001. http://www.pinpointco.com/.
5. T. Darrell, G. Gordon, M. Harville, and J. Woodfill. Integrated person tracking using stereo, color, and pattern detection. In *Conference on Computer Vision and Pattern Recognition*, pages 601–608. IEEE Computer Society, June 1998.
6. Lance Doherty, Kristofer S. J. Pister, and Laurent El Ghaoui. Convex position estimation in wireless sensor networks. In *Proceedings of IEEE Infocom 2001*, volume 3, pages 1655–1663. IEEE, IEEE Computer Society Press, April 2001.
7. Dieter Fox, Wolfram Burgard, Hannes Kruppa, and Sebastian Thrun. A probabilistic approach to collaborative multi-robot localization. *Autonomous Robots*, 8(3):325–244, June 2000.
8. Andy Harter and Andy Hopper. A distributed location system for the active office. In *IEEE Network*, pages 62–70. IEEE Computer Society Press, January/February 1994.
9. Andy Harter, Andy Hopper, Pete Steggles, Any Ward, and Paul Webster. The anatomy of a context-aware application. In *Proceedings of the 5th Annual ACM/IEEE International Conference on Mobile Computing and Networking (Mobicom 1999)*, pages 59–68, Seattle, WA, August 1999. ACM Press.
10. Jeffrey Hightower. Spoton: Indoor location sensing based on RF signal strength. Website, 2001. portolano.cs.washington.edu/projects/spoton/.
11. Jeffrey Hightower, Roy Want, and Gaetano Borriello. SpotON: An indoor 3d location sensing technology based on RF signal strength. UW-CSE 00-02-02, University of Washington, Department of Computer Science and Engineering, Seattle, WA, February 2000.
12. Starlink Incorporated. DGPS explained. Website, 2001. http://www.starlinkdgps.com/dgpsexp.htm.
13. Chalermek Intanagonwiwat, Ramesh Govindan, and Deborah Estrin. Directed diffusion: A scalable and robust communication paradigm for sensor networks. In *Proceedings of the Sixth Annual International Conference on Mobile Computing and Networks (MobiCom 2000)*, pages 56–67, Boston, MA, August 2000. ACM Press.
14. Scott Klemmer, Sarah Waterson, and Kamin Whitehouse. Towards a location-based context-aware sensor infrastructure. Course Project, 2001.
15. John Krumm, Steve Harris, Brian Meyers, Barry Brumitt, Michael Hale, and Steve Shafer. Multi-camera multi-person tracking for easyliving. In *IEEE Workshop on Visual Surveillance*, pages 3–10. IEEE Press, July 2000.
16. RF Monolithics. Tr1000 916.50 mhz hybrid transceiver datasheet, 2001. www.rfm.com.
17. DARPA Information Technology Office. Sensor information technology. Website, 2001. www.darpa.mil/ito/research/sensit/.

18. Robert J. Orr and Gregory D. Abowd. The smart floor: A mechanism for natural user identification and tracking. In *Proceedings of the 2000 Conference on Human Factors in Computing Systems (CHI 2000)*, The Hague, Netherlands, April 2000. ACM.
19. Nissanka B. Priyantha, Anit Chakraborty, and Hari Balakrishnan. The cricket location-support system. In *Proceedings of MOBICOM 2000*, pages 32–43, Boston, MA, August 2000. ACM, ACM Press.
20. Scott Y. Seidel and Theodore S. Rapport. 914 mhz path loss prediction model for indoor wireless communications in multifloored buildings. 40(2):207–217, February 1992.
21. Roy Want, Andy Hopper, Veronica Falcao, and Jon Gibbons. The active badge location system. *ACM Transactions on Information Systems*, 10(1):91–102, January 1992.
22. Roy Want, Bill Schilit, Norman Adams, Rich Gold, Karin Petersen, David Goldberg, John Ellis, and Mark Weiser. The parctab ubiquitous computing experiment. In Tomasz Imielinski, editor, *Mobile Computing*, chapter 2, pages 45–101. Kluwer Publishing, February 1997. ISBN 0-7923-9697-9.