# RF Time of Flight Ranging for Wireless Sensor Network Localization

Steven Lanzisera[1], David T. Lin[1], Kristofer S. J. Pister[1]

[1] University of California, Berkeley
Berkeley, CA 94720
{slanzise,dtlin,pister}@eecs.berkeley.edu

***Abstract –*** *A simple system for measuring the peer to peer radio frequency time of flight between two identical sensor motes for distance measurement is presented. This scheme uses a 2.4 GHz radio, simple real time processing, and offline range extraction. Methods for reducing error from clock offset and multipath propagation are presented and implemented on prototype hardware. Measurement results are presented including measurements taken in a coal mine. Typical ranging accuracies are between 1* $m_{RMS}$ *and 3* $m_{RMS}$.

## 1 Introduction

Sensor networks for monitoring equipment and assets currently rely on wired infrastructure to provide power and transfer data. The high cost and low flexibility of this wired infrastructure limits the application space of sensor networks. Wireless sensor networks (WSNs) promise to alleviate these problems, but adoption has been slow due to reliability concerns and, in part, due to the lack of localization technologies. Advancements in wireless mesh networking have increased reliability to a point where large scale networks are possible.

Localization is the process though which motes in a network are associated with their physical location rather than a network address. Self localization of wireless motes is an enabling technology for both very large networks and for networks with movable motes. As the cost of motes decreases and the size of networks increase, the cost of surveying each node's location at deployment will become a significant contributor to the deployment cost [1]. Automatic location discovery is also critical for "sprinkle deployments" desired for military and environmental monitoring applications [2]. For many of these applications, cooperative localization between individual motes rather than with base stations is required. The location accuracy required varies by application. Asset management and other tracking applications may require accuracy on the order of 1m to find a laptop or record file in an office building or hospital, several meters to find a person in a mine, or tens of meters to find a cargo container in a shipping yard.

Localization consists of two phases. The first phase consists of measuring a relationship between a set of known locations and the device with unknown location. The relationship of interest is typically either the distance between nodes or direction from one node to the other. The second phase is taking this information and turning it into a location that could be plotted on a map. This second phase has been studied in depth for sensor networks, and will not be discussed further in this paper [3,4]. A number of significant research efforts have produced WSN localization technologies. Most of these have focused on providing solutions for the first generation of motes such as the Mica mote [5]. The second generation mote is a device that contains a transceiver, microcontroller and memory all on a single chip reducing energy consumption and cost significantly [6]. These highly integrated devices will soon incorporate more sensors and advanced localization modules, and further study of core localization technologies for these devices is required.

Measuring the radio frequency time of flight (RF TOF) of a message traveling from one node to another can provide range information. RF TOF measurements are challenging because of the high signal speed, multipath (MP) propagation, and low tolerance for clock synchronization error. The primary advantages of RF TOF measurements are small hardware overhead, good wall penetration, and the potential for meter level location accuracy.

This paper presents a simple scheme for measuring RF TOF between two identical wireless sensor motes, and this work is intended for integration onto a WSN mote ASIC to allow peer to peer ranging. A method for mitigating pair-wise clock offset and a frequency hopping method for reducing the effects of MP propagation are introduced. The effects of varying important system parameters for indoor systems are presented. A prototype has been implemented to demonstrate the technique, and ranging measurements with meter level accuracy for indoor and outdoor environments as well as in coal mine tunnels are shown. The bandwidth required is compatible with IEEE 802.15.4 radios and could be incorporated into future single-chip motes. Expected ASIC energy consumption will allow multiyear mote lifetimes although the prototype is not intended to demonstrate low energy performance.

The remainder of this paper is organized as follows: section 2 reviews localization technologies available to sensor networks; section 3 provides an introduction to RF TOF measurements and studies the major sources of measurement error; section 4 discusses the system level implementation issues and introduces the prototype platform; section 5 presents measurement results; and section 6 discusses conclusions and future directions.

## 2 WSN Localization Technologies

Various technologies have been proposed for providing localization in WSNs. Most solutions are aimed at first generation motes, and significant progress has occurred in this area. Solutions for second generation, highly integrated motes have received less study. WSNs can use GPS to orient the network onto the global coordinate system if part of the network is outdoors. At 100's of mJ to a few Joules for the first location fix and accuracy of 10's of meters makes this an unsuitable solution for general use [7]. RF received signal strength (RSS) measurements have been used as a surrogate for a range sensor, but multipath fading makes this technique unsuitable for most low density applications. The simple implementation of RSS measurements makes it an attractive solution when only coarse geolocation is required [2,8]. Acoustic methods have become quite popular because of the high accuracy attainable as well as the ability to work with first generation hardware. This technique may not see wide use in second generation hardware because of the difficulty in integrating the components and the high energy required to drive a speaker [9]. When very precise positioning is required, however, acoustic methods will continue to be used. Ultra-wideband (UWB) transceivers have the potential to provide highly accurate localization. Accuracy comparable to acoustic techniques has been reported, and energy consumption of these transceivers can potentially compete with narrowband transceiver. Low power UWB transceivers have been demonstrated recently, but immunity to strong, narrowband interference and communication range remain significant issues for these devices [10]. For applications purely driven by geolocation and where strong interference can be minimized, this technology provides promise [11]. The radio interferometric positioning system is creative work that provides high accuracy positioning (10 cm) in low MP environments using the simple transceivers available on first generation motes. This technique is transferable to second generation devices, but the MP performance is unproven [12]. RF time of flight measurements have been demonstrated, but work has been largely limited to wide bandwidths and high power devices [13,14]. Optimization of RF TOF for WSNs has recently received attention with some interesting results in the wideband signaling domain although a full system was not implemented [15]. Ranging accuracy for these RF TOF methods is between 1 and 3 $m_{rms}$.

## 3 RF Time of Flight Ranging

RF time of flight (TOF) ranging is an attractive option for WSNs. An RF TOF system can require little hardware overhead and achieve meter level accuracy in difficult environments with the same transceiver used for data communication and simple signal processing blocks. RF TOF ranging can occur in short bursts and in a frequency hopped fashion thereby reducing the chance of interference and unwanted detection. Errors in RF TOF ranging measurements are caused primarily by interference from other signals, noise, or MP propagation. Other factors can systematically corrupt ranging accuracy such as clock offset and clock drift.

### 3.1 Background

Two classes of RF TOF measurement systems exist. The first is a scheme where some number of significant devices have highly accurate, synchronized clocks. In the simplest case, a signal is sent from a device with a known location and an accurate clock to another device with an accurate clock, and the departure time of the signal is compared to the actual time of arrival. The second type of RF TOF system is one in which only loose absolute time synchronization is possible. Ad hoc wireless networks are an example of this case. Synchronization on the order of microseconds is possible, but this is not fine enough for ranging purposes. Pair-wise roundtrip TOF measurements do not require absolute clock synchronization. By sending a ranging signal and waiting for a reply, the individual clock biases are subtracted away.

Some local area, wideband RF TOF ranging systems for wireless devices have been proposed. These systems use tens of MHz of bandwidth and are generally intended for use in police or fire fighter radios where energy consumption and bandwidth utilization are not of concern. Location accuracy has been reported in the range of 1 m to 3 m in indoor environments [13,14,15]. The work in [15] is intended for WSNs.

In bandwidth limited systems, measuring the TOF requires accurately resolving the phase offset of a signal. Pseudorandom noise (PN) codes are good candidate signals for measuring small phase offsets because the autocorrelation function of a PN code exhibits a single large peak that moves with phase offset. This peak is useful because a sequence of N values can be converted into a single feature with an effective signal to noise ratio (SNR) N times larger than that of the values used to construct it. The SNR enhancement is advantageous for noise limited ranging because accuracy improves with SNR [16,17].

### 3.2 Pair-wise Ranging Error Sources

Interference, primarily from MP propagation, causes the most significant measurement errors. MP interference occurs when the ranging signal reflects off objects in the environment and adds to the direct path signal at the receive antenna. Because this signal is perfectly in band and is a characteristic of the communication channel, it is impossible to filter it out or wait until it has gone away. The MP signals distort the received signal making the direct path TOF difficult to estimate.

Time drift between motes can contribute significant errors. In pair-wise ranging, the absolute time offset, the difference between $t = 0$ on one mote compared to at the other, is ignored. The required relative time synchronization, the absolute difference between the length of one second measured at one mote compared to at its partner mote, depends on the total time of the ranging operation. This systematic relative time drift between devices must be small enough that it does not contribute significant error to the ranging operation. For example, if a ranging operation lasts 100 µs, clock frequencies matched to better than 10 ppm will contribute less than a nanosecond of overall error.

### 3.3 Effect of System Parameters on Ranging Accuracy

Code length, code rate, and carrier frequency can be changed after deployment to impact range estimation. Limited study has occurred on the effects of these parameters on indoor, short distance ranging systems.

Code length is linearly proportional to the effective signal to noise ratio (SNR) after correlation. Increasing length is useful in situations where the ranging performance is limited by noise. Indoors, however, accuracy is limited by MP interference. In addition, increasing the code length increases the computation complexity of calculating the correlation function. Therefore, the minimum code length that meets noise requirements should be used.

The code chip rate, along with the transmit bandwidth, can be varied to improve MP performance. The use of PN codes can provide some rejection of MP induced error if the arrival time of the MP signal is greater than ½ the chip period, $T_c$. By reducing $T_c$ the maximum MP error contribution can be reduced and signals with shorter extra path delays can be rejected. It is commonly believed that doubling the bandwidth will reduce the error in all cases, but until $T_c$ becomes similar to the extra path delay of the MP signals of interest, increasing the chip rate has a negligible effect. This effect has been simulated and is shown in Figure 1. Signals with 1 Mchip/s and 5 Mchips/s have the same performance, and the signal transmitted at 10 Mchips/s provides a small improvement. Further increases in bandwidth will reduce the error as expected. Sufficiently large bandwidths will improve performance at the expense of transceiver power and susceptibility to interference. Unless a large bandwidth can be used, bandwidth can be reduced for better energy and interference performance.

It has been shown that MP effects on received signal power are frequency dependent [18]. This frequency dependence is the result of interference between the different signal paths at the receiving antenna. As the frequency of the transmitter changes, the path length in terms of number of wavelengths is also changing on each path. Because the path lengths are changing at different rates for each path, the resulting interference relationship is

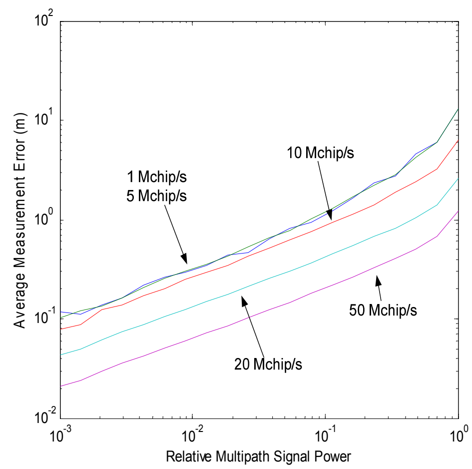


Figure 1: Simulated ranging error as a function of multipath signal strength and bandwidth

frequency dependent. This frequency dependence can be used to reduce the effect of MP interference.

In the noise limited case, changing these parameters will affect the ranging accuracy. According to the Cramer-Rao bound for the accuracy of an unbiased estimator, the variance of an RF TOF measurement is bounded by:

$$\sigma_{TOF}^2 = \frac{1}{8\pi^2 \cdot SNR \cdot \sqrt{\alpha} \cdot BW^2 \cdot N} \tag{1}$$

Where SNR is the average SNR at the two transceivers, α is the number of code copies averaged, BW is the occupied spectral bandwidth, and N is the number of chips in the PN code [17, 16]. Given this bound and the effect these parameters have on multipath performance, a set of system parameters can be chosen for nominal operation.

# 4 Proposed RF TOF Ranging System

## 4.1 Overview of Ranging Operation

For the purposes of this discussion, two motes, A and B, are involved in a ranging operation and have agreed to perform the operation at a given carrier frequency. The process consists of an online measurement phase and an offline range extraction phase.

The measurement phase occurs in real time and is shown in figure 2. Any timing offsets that occur in this phase can affect the resulting TOF measurement. The system uses an event clock (EC) with the same period, $T_{EC}$, as the ranging sequence length to ensure fidelity as will be described in section 4.2. The motes first become time synchronized to better than $\pm T_{EC}$. Mote B's EC will either be early or late compared to mote A's EC, and the system timing must account for this variation. Figure 2 shows examples where mote B's EC is $\frac{1}{2}T_{EC}$ earlier than perfect synchronization and where mote B's EC is $\frac{1}{2}T_{EC}$ later than perfect synchronization. These two examples are shown for illustration only, and there is only one mote B in a ranging measurement.

After synchronization, mote A waits for its next EC edge and then sends K copies of an N symbol ranging signal modulated on an RF carrier. Mote B waits for 2 EC edges and then receives K-2 copies of the signal, demodulates it and averages the K-2 copies so that one

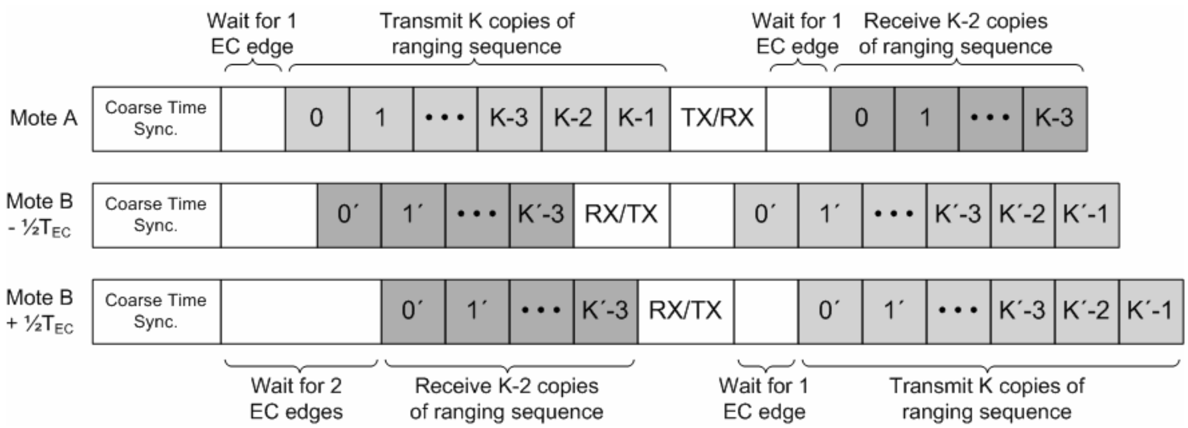


Figure 2: Example of complete measurement phase including examples with mote B's event clock both leading and lagging Mote A's event clock

circularly shifted copy of the sequence is stored locally. Note that mote B does not attempt to resolve the time of arrival of the signal; it only demodulates and averages the signal. The averaged received signal is then used as the ranging signal and is sent from mote B to mote A in the same manner as sent from A to B. After mote A has received and averaged the signal sent from mote B, both nodes turn off their transceivers and any dedicated hardware. No significant digital or analog signal processing has occurred on the signals up to this point. Access to the signals at the physical layer is required in order to ensure signal integrity thus limiting this technique to use in future $2^{nd}$ generation motes.

The range extraction occurs when the motes are not communicating. The method for this extraction can be based on other system requirements such as allowable hardware complexity, latency, energy consumption, etc. The range extraction is mathematically simple, and it can be implemented on the mote or the measurement data can be transmitted to a base station. Range extraction occurs as follows. First the cross correlation between the received signal and the local signal is calculated. The result is compared to a rough mask to throw away unreasonable measurements. Then the peak of the correlation function is found. The minimum achievable error is bounded by two factors. The first is a limit from noise, communication bandwidth, and relative clock synchronization. The second is from the sample rate of the signals used in the correlation process. Interpolating the ranging signal can increase the accuracy of the result up the level set by the first limit.

### 4.2 Minimizing Ranging Error

This RF TOF system is intended for low energy ranging in an ASIC wireless sensor mote. A small portion of the system is timing critical and must be implemented in a fashion with consistent latency. We propose a method for pair-wise ranging called Code Modulus Synchronization (CMS) that does not require either mote to determine the absolute phase offset of system clocks, the correlation function or the TOF in real time. This reduces the hardware overhead and measurement time by not requiring a real time correlator. Real time correlators are expensive from an energy standpoint because they either need to run at high sample rates or accumulate information over a long period of time with the radio on in order to resolve nanosecond TOFs. Reducing the measurement time is important because it

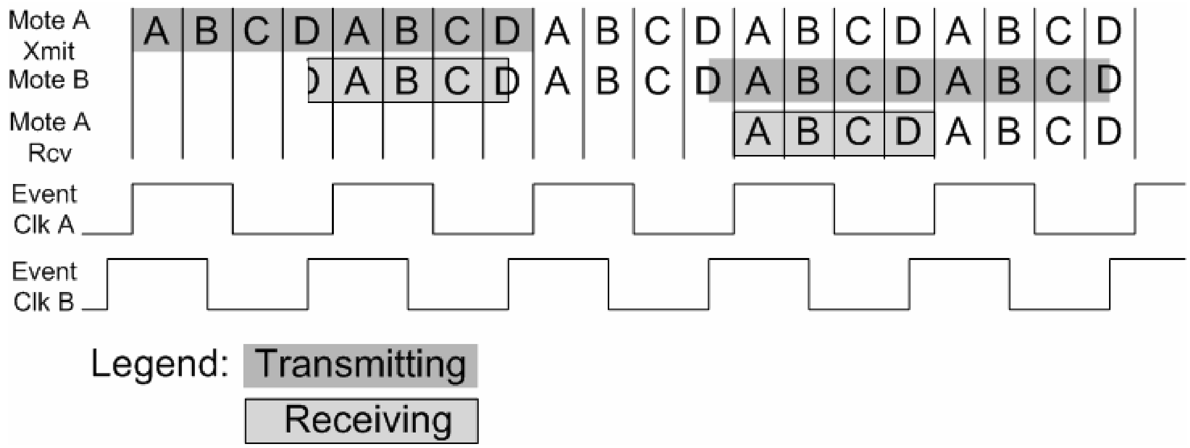


Figure 3: Code modulus synchronization method to ignore clock phase mismatch

relaxes the required relative clock synchronization.

In CMS, all major events are triggered by the system EC. The period of this clock is equal to one period of the PN code. Because the code is relatively short, this does not introduce significant latency into the system. The clock phases of the two motes are never synchronized, but the phase offset is effectively ignored. Figure 3 shows how this system ensures that the phase offset of the two ECs does not cause measurement error. This example demonstrates, for simplicity, a situation where the time of flight is zero and no averaging occurs. The code used here is a 4 symbol sequence ABCD. On the rising edge of mote A's EC, mote A starts to transmit two copies of its local code (line 1). Mote B is expecting this transmission and starts receiving on the rising edge of its EC (line 2). Note that mote B did not have a local copy of the code before it started receiving the incoming code. Mote B stops receiving on the next rising edge of its EC, and it knows it has received exactly one cycle of the PN code. Mote B does not know the phase offset of the code it received, and it never tries to determine this offset. Mote A stops sending the code after it has sent two copies. On the next rising edge of mote B's EC, mote B starts to send two copies of the code it received. Mote A starts to receive on the rising edge of its EC. Mote A receives one complete copy of the code (on line 3) that has no phase shift associated relative to its local copy of the code on line 1. Therefore the phase offset of the two ECs contributes no error to the system. In practice mote A must send more copies of its code to absorb the unknown absolute time offset and to allow for averaging. Similarly, B sends more copies of its code (see section 4.1). The only requirement is that the two motes have a similar sense of relative time. Because phase is the integral of frequency, observing the rate of change of the phase of a received, downconverted RF signal allows for quick and simple detection of small frequency offsets (relative time drift).

The primary method of multipath mitigation is to take measurements at multiple carrier frequencies, but the hardware is not specific to a particular mitigation strategy. The range extraction phase of the measurement can use more advanced methods of determining the TOF than just locating the peak. Work intended to improve the accuracy of GPS receivers for aircraft landing shows that the leading edges of features in the correlation function are unaffected by multipath interference. These leading edges are in the low SNR region of the correlation function making them hard to resolve, but averaging of many measurements can improve accuracy in multipath environments [19]. Carrier frequency hopping can reduce the effect of multipath. Changing the frequency, and thereby changing the path lengths in

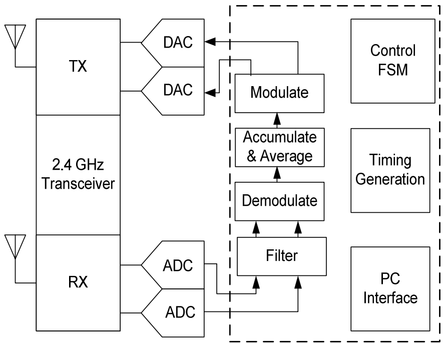


Figure 4: System block diagram as implemented on prototype hardware

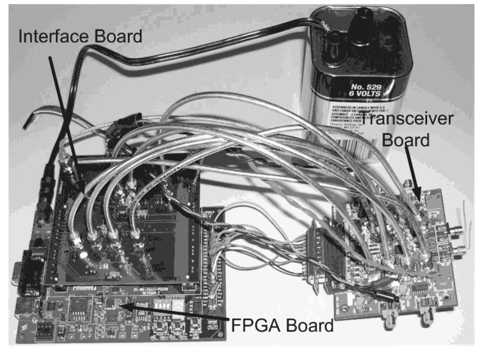


Figure 5: Photograph of prototype implementation

terms of wavelengths, will cause the phase relationships at the receiver to be different, and it has also been shown that the effect of multipath is phase dependent [13]. This frequency dependence can reduce the impact of multipath signals on ranging accuracy, and this work demonstrates that accuracy can be increased without locating an optimal carrier frequency.

### 4.3 Prototype Hardware

A prototype system has been implemented to demonstrate the viability of RF TOF ranging for WSNs. This prototype consists of commercially available components on PC boards. The block diagram, as implemented for this paper, is shown in figure 4. Figure 5 shows a photograph of one prototype mote, and it consists of a 2.4 GHz transceiver board, an analog to digital interfaces board, and an FPGA board. The use of a highly reconfigurable prototype platform was chosen to allow for testing of different configurations. The entire system can be integrated onto a single CMOS die as part of a second generation mote.

The required real time blocks are implemented on and controlled by the FPGA. In this implementation, these blocks are a 4 tap filter, a 5 bit digital demodulator, an 800 word accumulator, and a 5 bit digital modulator. The analog to digital interface elements are 25 MSps, 4 bit devices. After the measurement phase has been completed, the ranging data is downloaded to a PC for analysis.

Code length and code chip rate were chosen based on energy and performance requirements. After considering the factors discussed in section 3.3, the chiprate, code length, and averaging parameters were chosen to be 1Mchip/s, 8 chips, and 8 code copies, respectively. The remaining reduction in the measurement variance is accounted for by taking multiple measurements at different frequencies which is required to combat multipath effects. Not accounting for this final averaging, the noise limited accuracy is bounded by the result of (1) $\sigma_{TOF} = 3.7\, ns_{RMS}\,(1.1\, m_{RMS})$ for a 10 dB SNR and a 2 MHz precorrelation bandwidth.

## 5 Experimental Results

The prototype hardware has been used to take RF TOF measurements in different indoor and outdoor environments. Measurements inside rooms, in hallways and through walls, and in coal mine tunnels have been performed. Typical ranging accuracy indoors is approximately two meters. Measurement errors outdoors are typically less than a meter. In order to achieve this level of accuracy, multiple measurements for a given location are required.

Measurement results and the effect of carrier frequency on any individual measurement will be discussed. All measurements were done in the 2.4 GHz ISM band, and these results are similar to the more complicated, wideband approaches presented in [13-15].

## 5.1 Measurement Variance

The minimum standard deviation of a TOF measurement in this system is given by (1) as 3.7 $ns_{RMS}$. In order to determine how close this system approaches this bound, the two prototype units were placed in fixed locations and 1000 measurement were performed over an indoor channel. The standard deviation of these measurements was 9.7 $ns_{RMS}$. The bound is a lower theoretical limit, and the proposed method has an error standard deviation on the same order as the theoretical bound. Because the timing critical components are on an FPGA and sampling occurs on a different PC board, it is expected that an ASIC implementation would have a lower measurement variance. This variance is important because it shows the minimum number of measurements required to achieve a given accuracy.

## 5.2 Outdoor Ranging Results

The outdoor measurements were taken on a grassy field with the motes less than a foot above ground level. Three samples were taken at each of four different frequencies for a total of 12 measurements per plotted point in figure 6. The same carrier frequencies were used for each separation between motes. Estimation error is small in this case because strong multipath components are not present, but the largest errors are at the shortest ranges. Transceiver nonlinearity negatively affects measurement accuracy at the short ranges. The RMS error in this sample is 0.9 $m_{RMS}$ while the peak error is 2.3 m.

## 5.3 Indoor Ranging Results

The indoor environment used here is a concrete and steel frame building on the UC Berkeley campus. Measurements taken inside a room and through a wall have been performed, and an example measurement is shown in figure 7. All measurements here were taken at the same five carrier frequencies with three data points per frequency. The RMS error in this data sample is 1.8 $m_{RMS}$, and the maximum error is 3.4 m.

Hallway measurements are challenging because the many strong multipath components tend to cause significant estimation errors. The measurements shown in figure 8 were taken in hallway with a concrete wall and floor. All measurements were taken at the same ten carrier frequencies with three samples per frequency. The RMS error in this data sample is 2.6 $m_{RMS}$, and the maximum error is 5.5 m.

## 5.4 Ranging in a Coal Mine

Measurements were taken in an unused coal and silica mine. The structural rock in this mine is sandstone. Figure 9 shows a histogram of ranging error of individual measurements before the measurements from multiple frequencies have been averaged to produce the final ranging estimate. Multiple samples at each frequency have been averaged to reduce the impact of noise. These samples are approximately Gaussian with ($\mu$ = 1.5 m, $\sigma$ = 2.6 m), and the RMS error is 2.7 m. After averaging over frequency to reduce the measurement error, $\mu$ = 0.7 m, $\sigma$ = 1.2 m, and the RMS error is 1.7 m. Errors as large as 18 m are seen before averaging, and the maximum error is reduced to 5 m after averaging. The averaging technique presented reduces all of the parameters of interest.

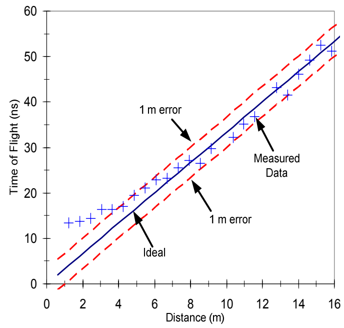


Figure 6: Outdoor ranging measurements with RMS error of 1 m

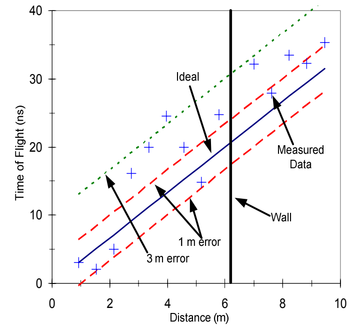


Figure 7: Indoor ranging measurements through a wall

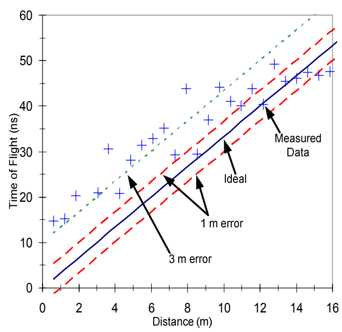


Figure 8: Ranging measurements in a hallway

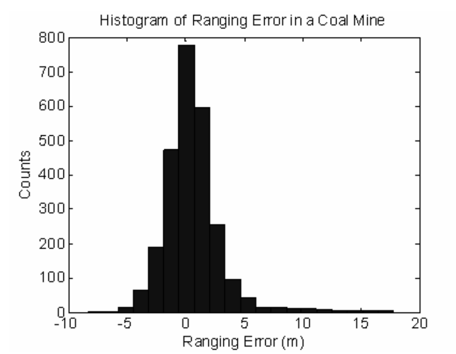


Figure 9: Histogram of ranging error in a coal mine adit (tunnel) before data averaging

### 5.5 Ranging Dependence on Frequency

Figure 10 shows the measurement error as a function of frequency for a fixed distance in a strong MP environment. Increasing the number of frequency points used can reduce error compared to samples at a single frequency. For example, the error at 2405 MHz is 24 m while the average error from 2430 MHz to 2480 MHz is less than 3 m. The periodicity that is observed in this figure is a function of the environment, and it will be different every time one mote moves to a new location. In environments where there are a few strong MP interferers, this sort of periodicity is commonly observed. Qualitatively, it is beneficial that if a few measurements are taken at a few frequencies and the results vary significantly, it will be beneficial to take more data points to reduce the error. The number of frequency points used is primarily a tradeoff between system longevity and accuracy, and it can be dynamically adjusted based on location or measurement variance.

## 6 Future Directions and Conclusion

Integrating this system onto a second generation mote will enable large scale networks to provide meter level location accuracy. Estimated energy consumption is 50 µJ per ranging operation [20,21].

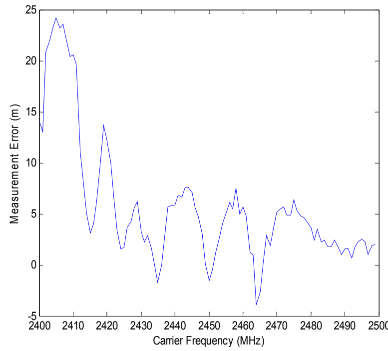


Figure 10: Example measurement of effect of variable carrier frequency on measurement

This work has shown a simple scheme for measuring the RF TOF for wireless ranging. Using this technique, a low cost, RF TOF based localization system can be included on wireless sensor motes with low cost, energy consumption and physical footprint. The demonstrated technique achieves outdoor measurements accuracy to within a meter. Indoor and in mine measurements typical have better than 3 meters accuracy and have been shown to work through walls and in difficult MP environments. This work achieves similar accuracy to previously published, wideband, high power indoor localization systems while using simplified hardware and small bandwidth.

## Acknowledgements

This material is based upon work supported by the National Science Foundation under Grant No. 0425914.

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