Harmonia: Wideband Spreading for Accurate Indoor RF Localization

Benjamin Kempke, Pat Pannuto, and Prabal Dutta
Electrical Engineering and Computer Science Department
University of Michigan
Ann Arbor, MI 48109
{bpkempke,ppannuto,prabal}@umich.edu

ABSTRACT

We introduce *Harmonia*, a new RF-based localization scheme that provides the simplicity, cost, and power advantages of traditional narrowband radios with the decimeter-scale accuracy of ultra wideband localization techniques. Harmonia is an asymmetric *tag* and *anchor* system, requiring minimal modifications to existing low-power wireless devices to support high-fidelity localization with comparatively modest infrastructure costs. A prototype Harmonia design offers location estimates with an average-case error of 53.4 cm in complex, heavy-multipath, indoor environments and captures location estimates at 56 Hz while requiring only 1.7 mA additional power draw for each tag and complying with all US UWB regulations. We believe this architecture's combination of accuracy, update rate, power draw, and system complexity will lead to a new point in the design space.

Categories and Subject Descriptors

C.3 [**COMPUTER-COMMUNICATION NETWORKS**]: Special-Purpose and Application-Based Systems

Keywords

Radio-frequency localization; Time difference of arrival; Multipath; Ultra-wideband; Software-defined radio; Band stitching

1. INTRODUCTION

Ultra-wideband (UWB) RF localization systems have been shown to achieve sub-meter localization accuracy in complex indoor environments, however, the realization of these systems often comes with drawbacks such as high system cost and complexity. We demonstrate that it is possible to achieve UWB-level localization accuracy in complex multipath environments using commercial narrowband radios. To achieve this, we employ a simple, low-power and low-cost modification to the transmit path of a narrowband radio, allowing for a deployable system that introduces little additional complexity to a conventional wireless tag.

Our system starts by augmenting a tag's narrowband transmitter with additional circuitry to spread its signal across over 1 GHz of instantaneous bandwidth. With this large amount of instantaneous bandwidth, the multipath environment can be measured at a much finer resolution than with the original narrowband signal, enabling more accurate localization. We achieve this wideband spreading by mixing the narrowband radio's output with a high-bandwidth and periodic source—a square wave. Square waves contain a wide range of harmonics, providing a simple source for a high-bandwidth signal and inspiration for our system name, *Harmonia*. To recover the UWB signal, Harmonia anchor nodes employ band stitching, a technique that sweeps a highly tunable narrowband radio across a wide frequency range and then recreates the observed wideband channel impulse response. As observing the entire UWB bandwidth at once is both costly and complex, band stitching enables Harmonia to only listen to a few harmonics at a time, significantly reducing the baseband ADC speed required. The Harmonia design addresses the two key challenges behind the adoption of UWB systems: the limited availability of inexpensive commercial tags and the high cost and complexity of UWB anchor nodes.

The Harmonia architecture includes an explicit asymmetry between tags—the devices being localized—and anchors—support infrastructure that performs the actual localization. This design respects the energy, area, and efficiency constraints of wireless tags. To keep tag complexity to a minimum, Harmonia localization uses time difference-of-arrival techniques, which enables localization without requiring any time synchronization between the tag and anchor.

To test the Harmonia concept, we build proof-of-concept hardware and a small two-tag four-anchor system. The tag/anchor asymmetry in Harmonia enables low-cost and low-power tag hardware, while imposing only modest burdens on the anchor hardware design. Our proof-of-concept uses USRPs [1] for anchors, however we envision that a dedicated anchor could be constructed for as little as $200. Similarly, our proof-of-concept tag utilizes an RF frequency synthesizer which has not been optimized for cost or power. Initial measurements indicate that 50% of location estimates have an error of less than 39 cm. Localization estimates can be performed at 56 Hz and each estimate consumes an additional 0.091 mJ on top of that consumed by the pre-existing narrowband radio, enabling the addition of decimeter-scale localization services to current low-power wireless tags.

2. BACKGROUND AND RELATED WORK

RF localization is a well-studied topic with over two decades of prior research supporting mobile computing [2,3,4]. In this paper, we explore an emerging frontier—localizing small quadrotors indoors—that demands high accuracy, small size, low weight, and high update rate in cluttered environments. More broadly, quadrotors are an extreme example of a whole class of mobile assets that we may wish to localize and track indoors with low power and high fidelity.

HotWireless'14, September 11 2014, Maui, USA
ACM 978-1-4503-3076-3/14/09.
http://dx.doi.org/10.1145/2643614.2643616

The accuracy of RF localization primarily depends on the distribution of multipath components in the RF channel. Due to the prevalence of multipath in indoor environments, many RF localization techniques suffer from poor average localization accuracy, stemming from their inability to distinguish the line-of-sight (LoS) path from the other paths. Received signal strength (RSS) based approaches map the RSS indicator (RSSI) to a distance, using an inverse-square law [5] or location fingerprinting [6]. Unfortunately, in cluttered indoor environments, multipath induced fading results in large deviations in the RSS over short distances, affecting the quality of ranging and localization.

Because of the drawbacks of RSSI-based approaches, others have proposed directly measuring RF propagation time to multiple anchors as a proxy for range. Such localization systems determine node position using trilateration or multilateration [7]. Unfortunately, these approaches also suffer from multipath-induced error due to the ambiguity that arises when the LoS and non-LoS paths arrive with close temporal proximity. The ability to distinguish between the arrival time of the LoS path and any subsequent paths is directly related to the bandwidth of the transmitted signal, conferring an advantage to systems that utilize the greatest bandwidth. Harmonia does not employ two-way time-of-flight ranging due to often symmetric capabilities required of participating nodes. Rather, Harmonia's design reflects a fundamental asymmetry between tags and anchors, so Harmonia employs time-difference-of-arrival (TDoA), which supports simple tags and sophisticated anchors.

A third RF localization technique determines a node's position by measuring the angle-of-arrival (AoA) of the LoS path. These "beamforming" systems utilize triangulation to determine the node's position, relying on a precise placement of multiple antenna elements, and a mechanism to steer the resulting beam, which either can be performed online or in post-processing [8]. Again, localization accuracy is affected by multipath in indoor environments, as the angular resolution is directly related to the number of beamforming elements [9].

To address the errors that have their roots in multipath, a growing set of systems employ diversity, which has been shown to provide incremental improvements in localization accuracy. Diversity in space, time, and frequency all improve the accuracy of a single location estimate. Approaches which utilize diversity assume that observations of the RF environment change when one of these variables change.

Spatial diversity is achieved by either increasing the number of antennas (e.g. MIMO or switched antenna architectures) or moving a single antenna through space [10] to obtain multiple observations. Spatial diversity has been used in all of the aforementioned localization technology areas in order to average out the deleterious effects of multipath. If sufficient stability can be achieved and the position of a set of independent observations over time is accurately known, further accuracy can be obtained by implementing beamforming [8]. Although not currently used in the Harmonia design, spatial diversity could be added by, for example, increasing the number of antenna elements.

Temporal diversity operates under the assumption that the RF environment changes significantly across successive localization measurements. These changes can be associated with either movement of the tag under observation or changes in the multipath characteristics. Many approaches take advantage of time diversity through the combination of these successive measurements. Harmonia currently does not employ temporal diversity, however, time averaging the location estimates that Harmonia generates would improve localization accuracy at the expense of update rate.

Finally, frequency diversity techniques [11] aim to increase localization accuracy by increasing the total system bandwidth. With narrowband systems, this typically involves taking measurements across adjacent RF channels. Taken to the logical extreme, impulse response ultra-wideband (IR-UWB) systems [12] achieve large ($>$ 500 MHz) amounts of instantaneous bandwidth, which allows them to disambiguate the LoS and non-LoS paths [13, 14]. Unfortunately, this requires fast and sophisticated anchors that have commensurately high bandwidth to digitize and process the signals, driving up cost and complexity. Harmonia also achieves accuracy through frequency diversity, but unlike UWB, Harmonia employs band stitching to increase bandwidth.

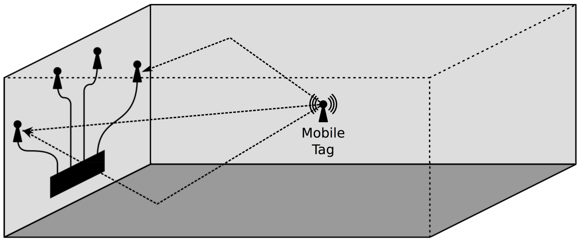


Figure 1: General infrastructure-based TDoA localization system architecture. TDoA localization systems lessen tag complexity by foregoing the need for accurate time synchronization between the tag and infrastructure. Harmonia targets TDoA to push as much system complexity as possible to the fixed-cost infrastructure.

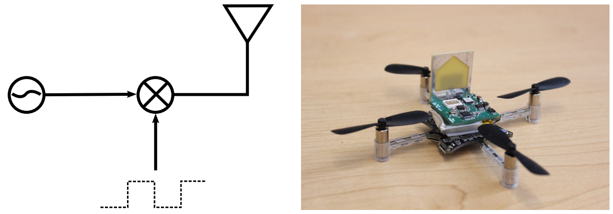
Narrowband radios which employ band stitching are able to observe bandwidths equivalent to those utilized in IR-UWB systems. Band stitching operates under the assumption that the received spectral components maintain close to constant phase throughout an extended observation window. If this condition holds true, an accurate reconstruction of high-bandwidth and periodic signals can be obtained by taking multiple narrowband observations at varying center frequencies.

The narrowband observations obtained during band stitching must be spaced closely enough in frequency in order to accurately observe all spectral components. Similarly, all narrowband observations must be completed quickly enough to avoid any deleterious effects from tag movement. Movement of the transmitting tag can affect the tag's perceived carrier frequency through Doppler effects. If no prior knowledge of the tag's movement can be taken into account, these Doppler effects will break the previously-stated assumption of constant spectral phase during the extended observation time. Despite these potential drawbacks, band stitching approaches utilizing these concepts have been shown to greatly improve localization accuracy in related narrowband systems [15].

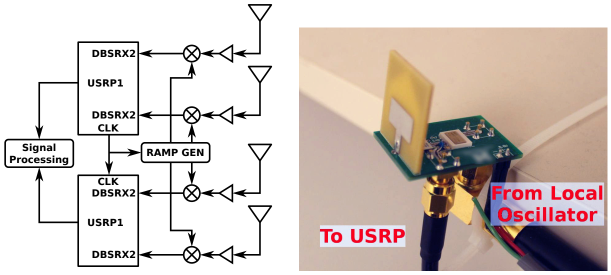
Harmonia employs band stitching and solves the two challenges—knowing phase and ensuring low latency—by mixing a square wave with a narrowband (sine) wave, thus creating harmonics across a wideband spectrum with known phase and zero band switching latency (on the transmitter size). On the receiving side, one or more low-bandwidth ADC(s) can recover the signal by quickly scanning across the bands, allowing Harmonia to construct a UWB representation of the channel frequency response (CFR).

3. ARCHITECTURAL APPROACH

Harmonia uses a time difference-of-arrival (TDoA) architecture for node localization, as shown in Figure 1. TDoA techniques benefit from a simple mobile node architecture, as a majority of the timing complexity is pushed to the anchor nodes. TDoA techniques also simplify the system by requiring no time synchronization between the tag and anchor nodes, at the cost of requiring a fourth anchor node to solve for the additional unknown (time).

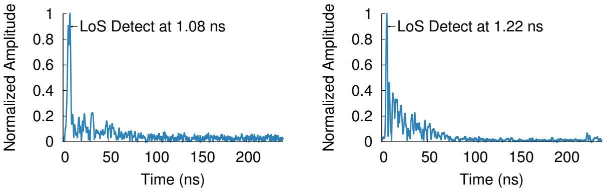


(a) Tag Architecture (b) Tag Realization

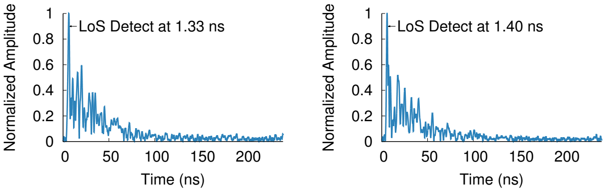


(c) Anchor Architecture (d) Anchor Realization

Figure 2: Harmonia tags and anchors. (a) Harmonia tags mix the output of a conventional narrowband radio with a high-bandwidth square wave, smearing the narrowband signal across over 1 GHz of bandwidth. (c) These UWB signals are received by the frequency-swept infrastructure to reconstruct the channel impulse response by band stitching. (b) and (d) are our prototype Harmonia tag and anchor respectively.



(a) Anchor 1 (b) Anchor 2



(c) Anchor 3 (d) Anchor 4

Figure 3: Measured Channel Impulse Response (CIR) at each anchor. These CIR measurements are obtained by deconvolving the received signal against that which was expected. Through observation of the CIR at each anchor, the time-of-arrival is calculated as the 50% height of the first distinguishable path's leading edge. Once the ToA is known at all four anchors, a location estimate can be obtained by applying TDoA localization concepts.

3.1 Tag Design

The Harmonia tags are designed to be as simple as possible while still allowing for an accessible COTS design. Tags consist of a narrowband radio for RF frequency generation, an RF mixer, a square wave oscillator, and discrete components for filtering the resulting signal to comply with US UWB regulations. A simplified architecture diagram for the location tag can be seen in Figure 2a. The narrowband radio is configured to transmit, power is applied to the square wave oscillator, and both are kept on as long as localization operations are required. Harmonia tags require no receive functionality, minimizing system complexity.

3.2 Anchor Design

Harmonia obtains timing estimates for the arrival time of the line-of-sight path through analysis of the channel impulse response (CIR). To obtain the CIR, each anchor needs to record the amplitude and phase information for each harmonic present in the bandwidth of interest. Our anchor design, shown in Figure 2c, uses a ramp generator to sweep across a wide range of narrowband frequencies, stitching them together to capture the complete signal. Once amplitude and phase information is known for each harmonic, the CIR can be obtained through a straightforward deconvolution against the expected signal generated by the tags.

4. PROTOTYPE AND EVALUATION

We implement a preliminary hardware design to test the Harmonia concepts. To generate the square wave on the mobile tag we use a simple 2 MHz CMOS oscillator (SG-210 STF), carefully chosen to have adequate rise and fall time in order to provide the rapid transitions necessary for high bandwidth utilization. We select a Mini-Circuits MAC-12GL+ mixer as it operates at the frequency of interest (5.8 GHz) and provides adequate bandwidth on its second intermediate frequency (IF) port. RF carrier generation is performed with a PLL (ADF4159) and VCO (RFVC1802).

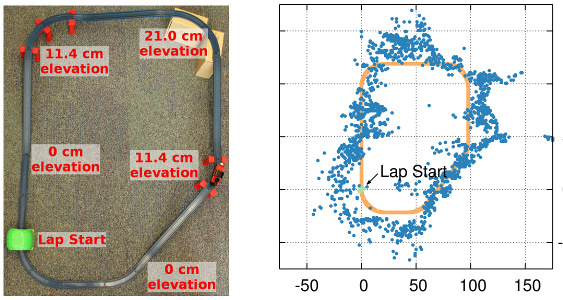
To quickly and synchronously sweep all four anchors across the bands of interest, we build a custom PCB based on the ADF4159 PLL to generate a centralized local oscillator (LO), which is split and distributed to the four anchors using low-loss coaxial cable. This LO signal is used locally at each anchor to mix the anchor antenna's output down to an intermediate frequency (IF). The IF signal is brought back to a central location where USRPs record independent observations of the tag's transmitted signal at each of the four anchors for post-processing.

Post-processing starts by measuring the amplitude and phase for each of the square wave's harmonics observed through the frequency sweep. Successive measurements in time are then combined by applying band stitching operations to reconstruct the entire frequency response of the tag's transmitted signal. As the transmitted signal is known, the wideband signal can be utilized to infer the CIR at each anchor through the well-known process of deconvolution.

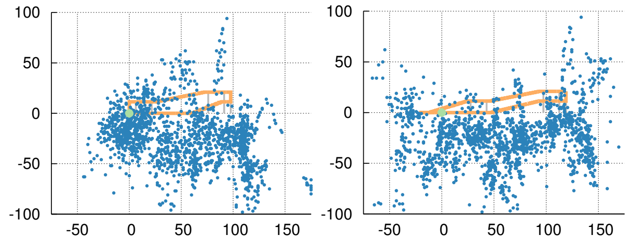
Analysis of the CIR is used to estimate the time of arrival of the incoming pulse. A simple heuristic of the 20% height of the first peak is utilized to estimate the time-of-arrival of the LoS path. Figure 3 shows the unique CIR at each anchor. Once the ToA is known for each anchor, the node's position can be calculated via multilateration.

As a preliminary evaluation, we place a Harmonia tag on a model train and capture location estimates as it progresses around the track. Although we eventually target quadrotors, we evaluate on a train track due to the difficulty of obtaining ground truth for flight paths. We are able to capture location estimates at a sampling rate of 56 Hz. The sampling rate is limited by the number of observations (32), the time spent at each observation (403 µs), and the switching time between observations (154 µs).

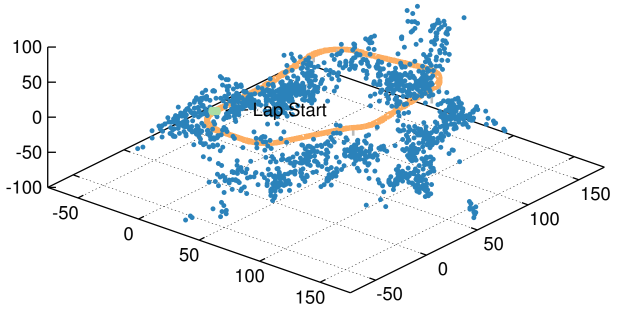
Figure 4 shows the layout of the train's course along with the reconstructed path for one complete lap and the error of Harmonia estimates. As the exact position of the tag in space and time is unknown when each sample is taken, we compute the optimistic error, that is the minimum distance from a Harmonia location estimate to the nearest point on the track. Figure 4a is the actual setup and



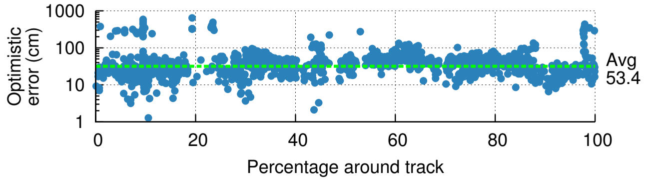
(a) Train Setup (b) Top View



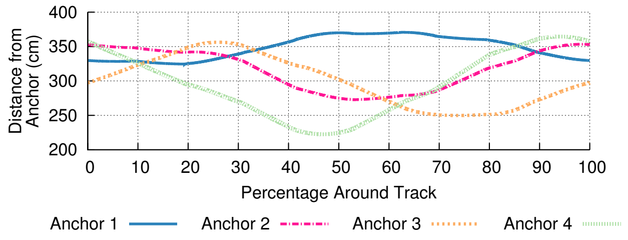
(c) Side View from X (d) Side View from Y



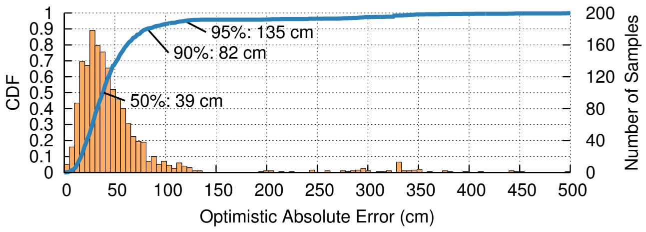
(e) Profile View



(f) Optimistic Error

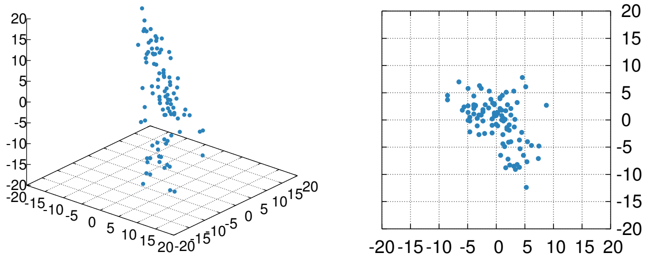


(g) Tag to Anchor Distance

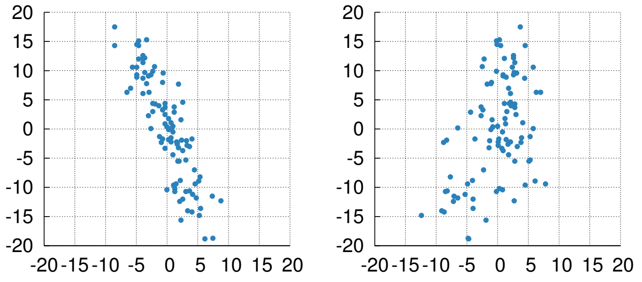


(h) Error CDF and Histogram

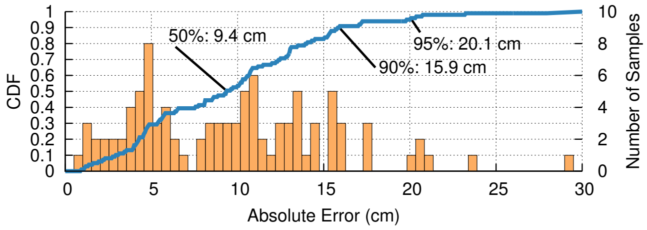
Figure 4: Preliminary evaluation of Harmonia. Location fixes, error estimates, and tag to anchor distances for one lap around the track.



(a) Profile View (b) Top View



(c) Side View from X (d) Side View from Y



(e) Error CDF and Histogram

Figure 5: Location measurements of a stationary Harmonia tag. Due to noise in the channel and measurements, a tag nominally at `(0,0,0)` shows up to 28.8 cm of error, with an average error of 9.45 cm.

Figures 4b to 4d show a point cloud of Harmonia location estimates around the actual track. Figures 4f and 4g show the error around the track and the distance from the tag to each anchor as the train progresses. A CDF and histogram of error are shown in Figure 4h, which finds that 50% of measurements are within 39 cm and 90% are within 82 cm.

As an initial step in exploring the Harmonia premise, we find these results very promising. Harmonia already achieves approximate parity with highly researched narrowband localization schemes and there a many low-hanging opportunities for improvement: i) as seen in Figure 5, our implementation is susceptible to noise, ii) our implementation requires some potentially fragile and error-inducing calibration, iii) our setup uses only the minimum number of anchors, even one additional multilateration constraint (anchor) can greatly improve accuracy, and iv) our carrier wave source (VCO+PLL) introduces greater phase noise than a typical radio.

5. DISCUSSION

Using square wave modulation, the maximum derivable CIR length for a square wave subcarrier frequency f is $\frac{3\times10^8}{2f}m$. For the 2 MHz square wave used for this system's evaluation, this corresponds to a maximum achievable CIR length of 75 m. If multipath within the environment is observed for longer than this amount of time, that is a path including reflections from tag to anchor exceeds 75 m, it is possible to see errors resulting from the interference of aliased multipath within the CIR. Decreasing the square wave frequency increases this length, however this has a poor side effect of significantly decreasing the amplitude of the high-frequency harmonics. Other approaches may choose to replace the square wave with pseudorandom noise (PN) codes which have better auto-correlation properties than the square wave itself.

The maximum usable range of the system is limited due to power limitations imposed by regional UWB regulations. Given these limitations and additional path losses, the estimated receive power for the lowest-power square wave spectral components at a 3 m distance is approximately -113 dBm. With thermal noise of -140 dBm, this allows for an SNR of 27 dB in line-of-sight conditions. Additional decreases in SNR due to receiver noise, multipath, interferers, and various incurred propagation losses can cause this number to decrease significantly. Future work will explore the maximum usable range for Harmonia in realistic indoor environments.

This transmission approach occupies the entire bandwidth continuously; however, the UWB regulations often allow for short bursts of higher instantaneous power as long as average power over a set time period remains the same. Other approaches to consider might explore additional tag complexity to synchronously track with the anchor node's sweep, allowing for faster and more accurate long-range location estimates.

Our optimistic error method returns the best possible result of Harmonia estimates, which may not be representative of the actual system performance. It is unclear, however, how to better establish ground truth estimates and measurements to evaluate a mobile tag.

6. CONCLUSIONS

Accurate indoor RF localization has eluded widespread adoption despite significant commercial activity. Part of the reason is that today's custom hardware and sophisticated anchor designs drive up the cost and complexity, hampering adoption. To address these challenges, we propose Harmonia, a new system that achieves UWB bandwidth utilization—and nearly commensurate accuracy—using narrowband radios, enabling a new design point consisting of simple tags and USRP-based anchors. The key insight is that location tags that mix the output of traditional narrowband radio with a square wave spread the radio's signal across a wide band—the many harmonics of the square wave. Fixed-location anchors perform localization through TDoA techniques and leverage a band stitching approach to minimize the baseband ADC sampling rate. This design point shows promise, achieving far better than the room-level accuracy prevalent today, and opening up the possibility of accurate localization to a diverse ecosystem of wireless tags, including low-power or even energy harvesting designs.

7. ACKNOWLEDGMENTS

This work was supported in part by the TerraSwarm Research Center, one of six centers supported by the STARnet phase of the Focus Center Research Program (FCRP), a Semiconductor Research Corporation program sponsored by MARCO and DARPA. This research was conducted with Government support under and awarded by DoD, Air Force Office of Scientific Research, National Defense Science and Engineering Graduate (NDSEG) Fellowship, 32 CFR 168a. This material is based upon work partially supported by the National Science Foundation under grants CNS-0964120, CNS-1111541, and CNS-1350967, and generous gifts from Intel and Texas Instruments.

8. REFERENCES

[1] Universal Software Radio Peripheral (USRP) X-Series, Ettus Research LLC. https://www.ettus.com/product/category/USRP-X-Series.

[2] Yanying Gu, Anthony Lo, and Ignas Niemegeers. A survey of indoor positioning systems for wireless personal networks. *Communications Surveys & Tutorials, IEEE*, 11(1), 2009.

[3] Hui Liu, Houshang Darabi, Pat Banerjee, and Jing Liu. Survey of wireless indoor positioning techniques and systems. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on*, 37(6), 2007.

[4] Zahid Farid, Rosdiadee Nordin, and Mahamod Ismail. Recent advances in wireless indoor localization techniques and system. *Journal of Computer Networks and Communications*, 2013, 2013.

[5] C. Alippi and G. Vanini. A RSSI-based and calibrated centralized localization technique for wireless sensor networks. In *Pervasive Computing and Communications Workshops*, 2006.

[6] P. Bahl and V. Padmanabhan. RADAR: An in-building RF-based user location and tracking system. volume 2, March 2000.

[7] Andreas Savvides, Heemin Park, and Mani B. Srivastava. The bits and flops of the N-hop multilateration primitive for node localization problems. In *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications*, WSNA '02, 2002.

[8] Jie Xiong and Kyle Jamieson. ArrayTrack: A fine-grained indoor location system. In *Usenix NSDI*, 2013.

[9] Constantine A Balanis and Panayiotis I Ioannides. Introduction to smart antennas. *Synthesis Lectures on Antennas*, 2(1):1–175, 2007.

[10] Branislav Kusy, Akos Ledeczi, and Xenofon Koutsoukos. Tracking mobile nodes using RF Doppler shifts. In *Proceedings of the 5th international conference on Embedded networked sensor systems*. ACM, 2007.

[11] Kaishun Wu, Jiang Xiao, Youwen Yi, Min Gao, and Lionel M Ni. Fila: Fine-grained indoor localization. In *INFOCOM, 2012 Proceedings IEEE*. IEEE, 2012.

[12] Kasun Maduranga Silva Thotahewa, Jean-Michel Redouté, and Mehmet Rasit Yuce. Hardware architectures for IR-UWB-based transceivers. In *Ultra Wideband Wireless Body Area Networks*. Springer, 2014.

[13] Time Domain PulsON 400 RCM. http://www.timedomain.com/p400.php.

[14] Ubisense Location Platform. http://ubisense.net/en/.

[15] Thuraiappah Sathyan, David Humphrey, and Mark Hedley. WASP: A system and algorithms for accurate radio localization using low-cost hardware. *IEEE Transactions on Systems, Man, and Cybernetics – Part C*, 41(2), March 2011.