Using RF received phase for indoor tracking

János Sallai*
Ákos Lédeczi*

Isaac Amundson*
Xenofon Koutsoukos*

Miklós Maróti†

Abstract

Today, RF based indoor node localization and tracking techniques predominantly rely on received signal strength (RSS), proximity information, or some sort of a priori mapping of the RF environment. However, due to nonideal RF propagation caused by effects such as reflection, refraction, scattering and multipath, as well as the dynamically changing environment, these solutions have limited accuracy. In this work, we investigate the feasibility of RF phase based tracking indoors. First, we present a fine-grained map of RF phase measurements taken in an office area: a harsh RF environment with windows, furniture and a steel door. Then, we present an approach to carry out one-dimensional tracking under such circumstances. Finally, we present preliminary experimental tracking results, with accuracy in the centimeter range, that justify the feasibility of the proposed technique.

Categories and Subject Descriptors

C.2.4 [**Computer-Communications Networks**]: Distributed Systems; C.3 [**Special-Purpose and Application-Based Systems**]: Real-time and Embedded Systems; J.2 [**Physical Sciences and Engineering**]: Engineering

General Terms

Algorithms, Experimentation, Theory

Keywords

Mobile Networks, Tracking, Localization

Acknowledgments

This work was supported in part by NSF grant CNS-0721604, ARO MURI grant W911NF-06-1-0076 and the TÁMOP-4.2.2/08/1/2008-0008 program of the Hungarian National Development Agency.

1 Introduction

Fine-grained localization and tracking of wireless nodes indoors still eludes us after years of sensor networks research. Range-based approaches, such as ultrasonic, acoustic or received signal strength are either expensive in terms of hardware or suffer from limited accuracy due to nonideal signal propagation indoors. Range-free approaches, such as RF proximity based localization or a priori mapping of the environment, in addition to being coarse grained solutions, are also prone to temporal changes in the environment [3]. While ultra-wideband (UWB) systems are more tolerant to multipath propagation than their RSS-based counterparts [9], and offer fine-grained localization with accuracy in the ten centimeter range, they have limited utility due to a mandate on maximum transmit power by the Federal Communications Commission (FCC). Also, UWB transceivers, as of today, are less power-efficient than traditional RF transceivers, due to the higher internal clock rates required to process a very high frequency RF signal.

In this paper, we investigate the indoor applicability of RF phase based approaches in general, and the radio-interferometric approach [6] in particular. RF phase based localization has long been in use: the LORAN system [5], a low-frequency RF maritime navigation system has been in service since World War II. In the wireless sensor networks domain, the radio-interferometric positioning system (RIPS) [8] is one representative of the RF phase based techniques. RIPS offers a set of compelling advantages. First, no additional hardware is required for ranging, since the communication hardware can be reprogrammed to collect the phase measurements. Second, the attainable ranging precision is a fraction of the carrier's wavelength, since the measured quantity is related to the phase of the carrier sinusoid. Over all, the radio-interferometric technique has proved to be a convenient and cost-effective vehicle for sensor node localization. However, so far, few results [7, 4] have been published about its applicability indoors.

The paper is structured as follows. First, we explain how localization information can be obtained by measuring the received phase difference of signals originating from a pair of transmitters. Then, we argue that nonideal RF propagation effects, such as reflection, refraction, scattering and multipath, distort the received phases, which cause existing techniques that work outdoors to fail indoors. To investigate the reasons for this, we present a map of received RF phase differences (collected using the radio-interferometric approach) measured in an indoor office environment. Based

---

*Institute for Software Integrated Systems, Vanderbilt University, 2015 Terrace Place, Nashville, TN 37203, USA

†Bolyai Institute, University of Szeged, Szeged, Hungary

HotEmNets 2010, June 28–29, 2010, Killarney, Ireland

on the mapping results, we propose a one-dimensional indoor tracking approach and present experimental tracking results.

2 Principle of RF phase difference based positioning

The principle of RF phase difference based positioning is closely related to that of time difference of arrival (TDOA) based techniques. A constant time difference of reception of signals from two transmitters constrains the location of the receiver to a hyperbolic curve. That is, if the time difference of reception and the locations of the transmitters are known, the position of the receiver can be determined to be somewhere on a particular hyperbola, the foci of which are the transmitter's locations, where the time difference is constant. More precisely, it is constrained to a particular *arm* of the hyperbola, and it is the sign of the time difference that designates which arm should be considered. Assuming ideal RF signal propagation, the time difference is linearly proportional to the distance difference from the transmitters.

In practice, however, accurately measuring the arrival time of RF signals is often complicated. Since the radio signal travels approximately 300 meters in a microsecond, localization accuracy on the meter scale requires measurement accuracy of nanoseconds. The alternative, more commonly used approach is measuring received phase instead. The received phase is also a function of the distance the RF signal travels from the transmitter to the receiver, however, this function is not invertible due to periodicity: if a given phase difference φ is measured at a position where the distance difference from the transmitters is d, the phase difference at positions with distance difference $d + k\lambda$ is also φ (where k is an integer and λ is the wavelength of the transmitted signal). Therefore, a constant phase difference of the received signals from a pair of transmitters constrains the location of the receiver to not just one, but a set of hyperbolic curves. Formally,

$$(d_{R,Tx_1} - d_{R,Tx_2})\ mod\,\lambda \;=\; \varphi\,\frac{\lambda}{2\pi} \tag{1}$$

where d_{R,Tx_1} and d_{R,Tx_2} are the receiver's distances from the two transmitters, respectively, φ is the measured phase difference and λ is the signal's wavelength. For instance, Figure 1 shows the hyperbolic curves where the received phase differences are zero. In this specific setup we assume that the distance between the transmitters is 12ft, and that the transmitted signal's wavelength is 2.45ft. The hyperbolic curves correspond to $-4, -3, \ldots, 3$ and 4 times the 2.45ft distance difference from the pair of transmitters, respectively. While one pair of transmitters is not enough to fix the receiver's position using this technique, multiple measurements involving different pairs, and optionally using other information such as previous/estimated position, are sufficient to track the receiver.

Subsequent results in this paper, both simulation and experiments, use a radio-interferometric measurement approach to acquire received phase differences from a pair of transmitters, as described in [1]. The technique, published in [8], involves two nodes transmitting continuously at close frequencies, creating a beat signal, the phase of which that can be reliably measured using simple devices, such as the Berkeley mica2 motes we used in the experiments described below. It has been shown in [8] that for transmitters T_1 and T_2, and receivers R_1 and R_2, the difference between the phase of the beat signal measured at R_1 and R_2 is related to a linear combination of pairwise distances between the nodes:

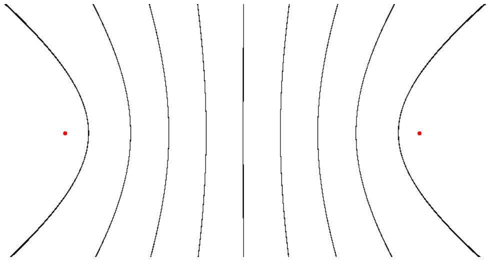

Figure 1. Simulated map of zero expected received phase difference. The black hyperbolic curves represent the set of points where the expected phase difference is zero. The red dots are the transmitters' locations, positioned 12ft apart. The wavelength is 2.45ft.

$$\varphi\frac{\lambda}{2\pi} \;=\; (d_{T1,R1} - d_{T2,R1} + d_{T2,R2} - d_{T1,R2})\ (mod\,\lambda) \tag{2}$$

where φ is the difference of phases observed at R_1 and R_2, λ is the wavelength of the carrier frequency, and $d_{A,B}$ is the Euclidean distance between nodes A and B. If the positions of nodes T_1, T_2 and R_2 are known, this equation can be rewritten as

$$c \;=\; (d_{T1,R1} - d_{T2,R1})\ (mod\,\lambda), \tag{3}$$

where c is the sum of a known constant distance difference and the measured phase difference:

$$c \;=\; (\varphi\frac{\lambda}{2\pi} + d_{T1,R2} - d_{T2,R2})\ (mod\,\lambda), \tag{4}$$

Notice, that Eq. 3 is an equation of an arm of a hyperbola, similar to Eq. 1 for the non-interferometric RF phase difference based localization. That is, we can use the radio-interferometric approach to measure what the phase difference of signals transmitted by T_1 and T_2 is at receiver R_1, with the help of an auxiliary receiver R_2 at a known location.

3 Challenges

While the RF phase based technique provides an elegant way to localize or track mobile receivers, its accuracy, and consequently, its applicability, has been limited by various factors. Apart from the attainable precision of phase measurement and time synchronization, the precision of the localization using the above technique greatly depends on the RF signal propagation patterns in a particular environment. Clearly, ideal RF propagation that is free from multipath and fading very rarely exists in reality. LORAN, being a maritime navigation system, operates in a predictable RF environment. The transmitters are located along the shoreline, while the receivers are on the sea, therefore the signal propagation is mostly free of reflections from objects of size comparable to the wavelength. Of course, ground reflection and skywaves, that is, ionospheric reflections must be accounted for, however, these multipath effects are deterministic: the elevation of the transmitters and receivers, as well as the height of the ionosphere, is known, and can be parameters of the location solver. RIPS also assumes a degree of predictability from the RF environment: it is resilient to erroneous measurement as long as the errors are uncorrelated, since the localization engine relies on finding a consistent measurement subset within the heavily redundant set of measurements.

Unfortunately, environments where objects of size comparable to the radio wavelength are the norm, rather then the exception (i.e. urban terrain and indoor spaces) are particularly hard to handle. As the the ratio of the power of the (random) multipath signals and that of the direct line-of-sight signal increases, the measured phase at the receiver may exhibit significant inconsistencies with respect to the expected values arising from the free-space propagation model [2].

4 Simulation of received phase differences

What we are particularly interested in is the extent to which these inconsistencies manifest themselves indoors, and the particular regularities or patterns (if any) in the inconsistencies. Intuitively, we suspect that the following conditions may hold when the transmitters and receivers are both indoors, e.g. in the same room or office space:

- **LOS dominance.** At the receiver, the power of line of sight (LOS) signal dominates over that of the multipath signals.
- **Spatial locality.** Close by locations exhibit similar inconsistencies. That is, while the inconsistencies do exist, they do not change suddenly.

Unfortunately, conventional statistical signal propagation models are not applicable to such a scenario. Neither Rayleigh fading, which assumes no line-of-sight component, nor Rician fading, a model which does assume line-of-sight propagation alongside the multipath signals, capture spatial locality of received signal phases. Therefore, we opted to investigate the phenomenon in simulation.

The simulator we created computes the received signal strength and phase difference from a pair of transmitters. It uses a simple path loss model and models a finite number of reflections, but not refractions and scattering, at walls, floor and ceiling. The simulation incorporates the effects of multipath propagation to the received signal strength and phase difference calculations.

We simulated the received RF phase differences for a room that measures 15ft by 45ft. The two transmitters are positioned at (-6,-0.5) and (6,0.5), respectively, where the origin of the coordinate system is the center of the room. The attenuation on each wall, ceiling and floor is set to 1dB. The simulated transmission frequencies are 401.14Mhz and 401.1403MHz, respectively.

Figure 2 shows the simulation results. As we can see, the curves that should be hyperbolic according to Equation 1 are distorted. However, we observe that along and around the line connecting the two transmitters the overall trends does resemble the expected map, i.e. the set of hyperbolas. This suggests that LOS dominance and spatial locality may hold true for this region.

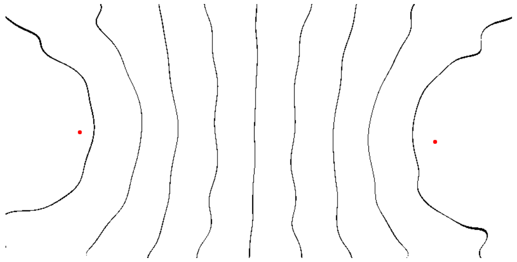

Figure 2. Simulated map of zero expected received phase difference assuming nonideal RF propagation. The black hyperbolic curves represent the set of points where the expected phase difference is zero. The red dots are the transmitters' locations, positioned approximately 12ft apart. The wavelength is 2.45ft.

5 Mapping the phase differences

To get an idea of how the hyperbolic curves, which represent the set of points where phase differences are constant, are distorted in a particular indoor environment, we created a map of them using the radio-interferometric approach.

The setup was the following. In a conference room of size 15ft by 45ft, we lay a 6ft by 4ft whiteboard on a table that was 3ft tall, roughly in the middle of the room. We used the center of the whiteboard as the origin of our coordinate system. The two radio-interferometric transmitters were placed 12ft apart, parallel to the 54-foot-long wall of the room and to the 6-foot-long side of the whiteboard, positioned at (-6,0) and (6,0), respectively. The transmit frequencies were set to 401.14Mhz and 401.1403MHz, respectively. An auxiliary receiver, required by the radio-interferometric ranging technique, was positioned approximately 24ft from the origin such that the phase difference measured at the origin be zero.

The receiver that we used to construct the map was initially positioned at the origin. From there, we followed the curve of zero phase difference towards the positive y and the negative y directions, marking the points on the whiteboard with a resolution of around 2in. When following the curve, we allowed for an error of 0.15 radians from zero, which is comparable to the inherent radio-interferometric measurement error for the given hardware, the Berkeley mica2 motes. Once a curve was mapped, we looked for another point on the x-axis that gave zero phase difference, and continued with mapping the corresponding curve, similarly. We continued this exhaustively until we mapped the curves of zero phase difference on the entire whiteboard.

The constructed map is shown in Figure 3. It is immediately visible on the map that the hyperbolic curves that we would theoretically expect are considerably distorted. This can be attributed to the fact that the experiment was carried out in a noisy RF environment, where reflections, refractions and multipath propagation heavily affect the received RF phases. This is not surprising, since the the room had windows with metallic window shades and under-the-window air conditioning units, a steel emergency exit door on one

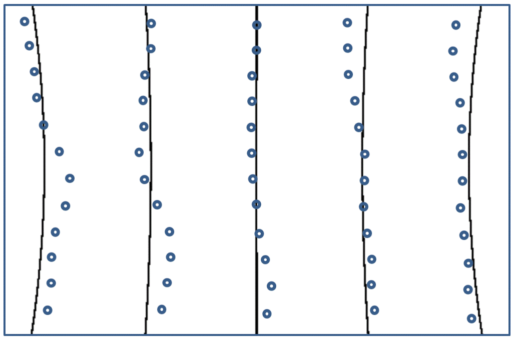

Figure 3. Measured map of zero phase difference. The black hyperbolic curves represent the set of points where the expected phase difference is zero. The blue circles represent discrete positions where the phase difference was measured to be zero.

side, and several wall-mounted whiteboards and a door on the other side.

We need to emphasize that the reason for the the fact that one of the mapped curves crosses the origin is that we purposefully positioned the auxiliary receiver to make that happen. We observed that the radio-interferometric measurements typically give inconsistent results indoors. That is, the measured phase difference, as a rule, does not correspond to the interferometric range (q-range). The most significant result of this mapping measurement is that LOS dominance and spatial locality do hold for the surveyed region in this particular environment.

6 Tracking

The RF phase mapping results suggest that it is possible to track a moving object equipped with an RF receiver device when the direction of its movement is perpendicular to the hyperbolic curves that correspond to the points of constant phase difference. If we can ensure that we measure frequently enough such that no more than 180 degree phase change occurs between consecutive measurements, then we can count the number of zero phase difference lines and unwrap the measured phases.

We set up a series of experiments to test this hypothesis. First, we set up a network of nodes (see Figure 4) on a table in a conference room of size 15ft by 45ft, similar to the RF phase mapping experiment. The two transmitter nodes were 12ft apart, at (-6,0) and at (6,0) respectively. A stationary auxiliary receiver, which is required to carry out the interferometric measurements, but the location of which is indifferent in this scenario, was located at (-24,0). Initially, we placed the receiver node to be tracked at (-1.3,-2). The experiment consisted of a series of 24 phase difference measurements, taken at locations 2in apart as we moved the receiver node along a linear trajectory to the end location (2.5,-2). The transmit frequencies were 401.14Mhz and 401.1403MHz, respectively, with corresponding wavelengths of 2.45ft. A displacement of 2in on this specific trajectory results in an approximately 3.7in change in the distance difference from the two transmitters, therefore, we expected that the phase wraps around once about every foot along the trajectory.

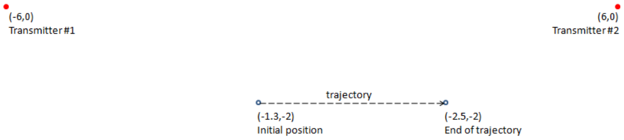

Figure 4. Setup of the *first* tracking measurement.

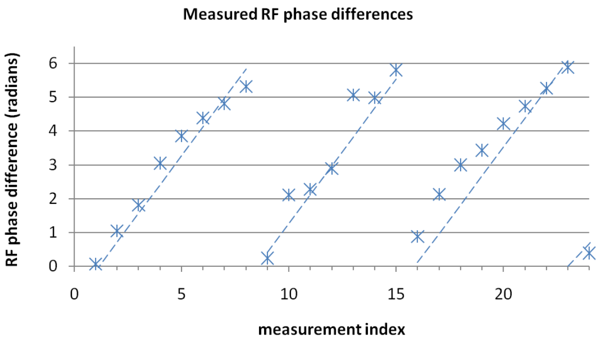

Figure 5. Measured phase differences along the *first* trajectory. The dashed line marks the approximate trend.

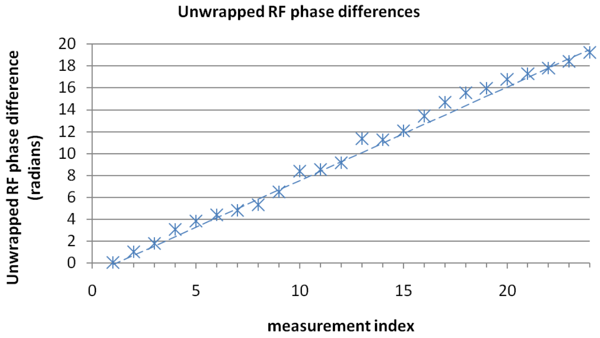

Figure 6. Unwrapped measured phase differences along the *first* trajectory. The dashed line marks the approximate trend.

Figure 5 shows the raw phase difference measurements with the approximate trendlines they follow. Clearly, such measurement data can easily be unwrapped, although it is noteworthy that the data is not monotonously increasing, as expected, due to the noisy RF environment. The unwrapped phase differences are shown in Figure 6. Figure 7 presents the unwrapped phase difference measurements converted to position. To calculate these positions, we assumed that the initial location of receiver node is known, and computed the locations along the trajectory from the cumulative phase change accrued, using the known (approximate) rate of phase change per unit displacement in this specific setup. The maximum absolute error was 4.48in and the standard deviation of the position errors was 1.53in.

We repeated the experiment with a different transmitter placement. The transmitters were again positioned 12ft

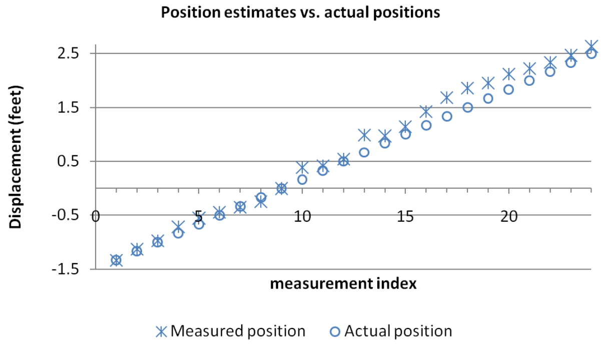

Figure 7. Expected and measured positions along the *first* trajectory.

apart, now at (0,-6) and at (0,6), respectively. The receiver was initially positioned at (2.5,-2) and was moved in 2in increments along a linear trajectory to (2.5,1.5). The rest of the setup remained unchanged. Movement by 2in along this specific trajectory results in approximately a 3.61in change in the distance difference from the transmitters.

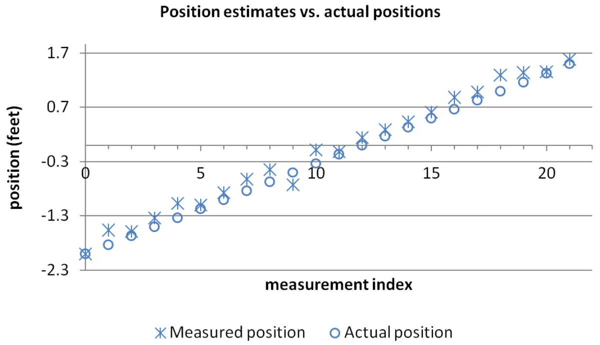

Figure 8. Expected and measured positions along the *second* trajectory.

The results are shown in Figure 8. Similar to the previous experiment, the measured phase differences were not monotonously increasing, but they were possible to unwrap. The locations were calculated, assuming the initial position to be known, from the cumulative phase changes, as described above. The maximum absolute error was 3.26in and the standard deviation of the position errors was 1.37in.

These results suggest that, even indoors, displacement can be estimated using the change in phase differences incured along a line parallel (and close) to the line connecting the two transmitters, that is, perpendicular to the hyperbolic curves. It is important to note that the computation of the individual locations along the trajectory did not take into account previous locations other than the initial position of the receiver. Therefore, this technique is not prone to error accumulation.

Of note, we also carried out several experiments when the node was moving *perpendicularly* to the line connecting the transmitters, that is, roughly parallel to the hyperbolic curves where we would expect constant phase differences. These experiments, however, provided mixed results. With the same 2-inch incremental movement along the trajectory, the phase differences were sometimes difficult to unwrap, the change in phase difference being close to π, and the results showed error on the order of feet from the expected values.

7 Conclusion and future work

We believe that the experiences with RF phase mapping and one-dimensional tracking described in this work convince the reader that such techniques, although with limitations, are, contrary to common belief, applicable to precise indoor localization and tracking. Although the one-dimensional tracking approach presented above has limited use cases (one could be tracking boxes equipped with active RF tags on a conveyor belt), we hope that our results will elicit further research in this direction. Such future work would include formalization of the RF conditions under which tracking is possible, using filtering techniques to smooth the tracked trajectories, techniques to bootstrap the tracking without the need for supplying an initial location, and extending the technique to work in two and three dimensions.

8 References

[1] I. Amundson, J. Sallai, X. Koutsoukos, and A. Lédeczi. Radio interferometric angle of arrival estimation. *In Proc. of EWSN*, Feb. 2010.

[2] B. Babjak, I. Biro, A. Magori, and B. Eged. Implementation and calibration of multi-channel receiver platform for phased-array reception. *19th International Wroclaw Symposium and Exhibition on Electromagnetic Compatibility*, june 2008.

[3] M. Bal, M. Liu, W. Shen, and H. Ghenniwa. Localization in cooperative wireless sensor networks: A review. *International Conference on Computer Supported Cooperative Work in Design*, 0:438–443, 2009.

[4] H.-L. Chang, J.-B. Tian, T.-T. Lai, H.-H. Chu, and P. Huang. Spinning beacons for precise indoor localization. In *Proc. of ACM Sensys*, 2008.

[5] R. L. Frank. History of loran-c. *Navigation: Journal of the Institute of Navigation*, 1982.

[6] B. Kusý, G. Balogh, P. Völgyesi, J. Sallai, A. Nádas, A. Lédeczi, M. Maróti, and L. Meertens. Node-density independent localization. *In Proc. of IPSN/SPOTS*, Apr. 2006.

[7] A. Ledeczi, P. Volgyesi, J. Sallai, B. Kusy, X. Koutsoukos, and M. Maroti. Towards precise indoor rf localization. In *HOTEMNETS'08*, Charlottesville, VA, 06/02 2008.

[8] M. Maróti, B. Kusý, G. Balogh, P. Völgyesi, A. Nádas, K. Molnár, S. Dóra, and A. Lédeczi. Radio interferometric geolocation. *In Proc. of ACM SenSys*, Nov. 2005.

[9] D. Young, C. Keller, D. Bliss, and K. Forsythe. Ultrawideband (uwb) transmitter location using time difference of arrival (tdoa) techniques. *Signals, Systems and Computers, 2003. Conference Record of the Thirty-Seventh Asilomar Conference on*, 2:1225–1229 Vol.2, 9-12 Nov. 2003.