DIRECTIONAL BEACON BASED POSITIONING SYSTEM USING RF SIGNALS

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ABSTRACT

We present the implementation of a directional beacon based positioning algorithm using radio frequency signals. This algorithm allows each mobile node to compute its position with respect to a set of reference nodes which are equipped with rotational directional antenna. The system implementation is based on the GNU Radio software platform with the Universal Software Radio Peripheral as the hardware component. Even though the technique needs some modification at the reference nodes in the form of a rotational directional antenna, we show that the mobile nodes do not need hardware modifications. We use maximum likelihood based amplitude estimation and least squares based line-of-sight time-delay estimation, to account for the presence of multipath components in the received signal. These techniques enable a more accurate estimation of the bearing of the mobile node with respect to each of the reference nodes. The proposed algorithm does not require any synchronization between the reference nodes and the mobile node. However, the reference nodes are assumed to be synchronized. We demonstrate the ability to obtain mobile node position estimates with sub-meter accuracy.

1. INTRODUCTION

Location awareness has found a number of applications ranging from commercial and residential (tracking people in assisted-living places and assets in a manufacturing facility) to public safety and military (tracking fire fighters and soldiers during their missions) [1].

The position of a node can be determined using a number of techniques such as Angle of Arrival (AOA) [2, 3, 4], Time of Arrival (TOA) [5], Time Difference of arrival (TDOA), or Received Signal Strength (RSS) [1]. Techniques based purely on signal strength are prone to inaccuracies and large variances in position estimates. TOA/TDOA based techniques when used with *narrowband* radio frequency (RF) signals do not provide sufficient accuracy whereas the use of ultrasound signals requires additional hardware and provides limited range. On the other hand, directionality based techniques can provide good accuracy with relatively inexpensive hardware. Our work is aimed at demonstrating a system that uses existing wireless network infrastructure (with very minimal modifications) to locate a mobile node. We use smart algorithms to overcome the low accuracy of the measured quantities.

Ultra-wideband (UWB) signals have been employed in position location systems [5, 6, 7, 8]. McGillem and Rappaport [3] were one of the earliest to propose the use of AOA information for positioning and navigation along with a system implementation demonstrating the technique. They used infrared beacons with a rotational optical receiving system to obtain angular measurements using beacons. Nasipuri presented a directionality based positioning scheme in [4]. Later in [9] they proposed a system implementation using rotating optical beacon generators and sensor nodes equipped with photo sensors. Shah and Tewfik in [2] presented an enhanced positioning scheme based on directional beacons using an efficient method for detecting the line of sight (LOS) component in the presence of multipath. Although many directionality based positioning techniques have been described in the literature, very few have presented practical system implementations, and even fewer have been presented based on RF signals. Using radio signals allows the opportunity to use the existing transceiver circuitry on wireless devices for positioning.

In this paper, we discuss the implementation of a directional beacon based positioning algorithm using narrowband RF signals. This algorithm allows each node to compute its position with respect to a set of reference nodes (RNs) which are equipped with rotational directional antenna. The system implementation presented is based on the GNU Radio software platform and uses Universal Software Radio Peripheral (USRP) as the hardware component. Even though the technique needs some modification at the RNs in the form of a rotational directional antenna, we show that the mobile nodes do not need hardware modifications. Another important advantage of the proposed algorithm is that it does not require any synchronization between the RNs and the mobile node. However, the RNs are assumed to be synchronized [10]. We use intelligent techniques such as maximum likelihood (ML) based amplitude estimation and least squares based line-of-sight (LOS) time-delay estimation, to estimate the bearing of the mobile node with respect to each of the RNs, in the presence of multipath components due to reflection etc. These techniques allow us to obtain enhanced position estimates with sub-meter accuracy.

The paper is organized as follows. Section 2 introduces the system model and the principle of localization using directional beacons. Section 3 presents the position location algorithm. In Section 4 we describe the hardware and software platform used for the prototype implementation followed by the details of the experimental set-up. In Section 5 we discuss enhanced ML amplitude estimation and LOS estimation in the presence of multipath using least squares based approach. Experimental results are presented in Section 6. Finally, we conclude with a few remarks in Section 7.

2. SYSTEM MODEL AND LOCALIZATION PRINCIPLE

This section describes the system model and the localization principle [2]. We refer to the nodes whose positions are known *a priori* as the reference nodes (RN) and nodes whose positions are unknown are mobile nodes. Consider a wireless network that contains three reference nodes RN-1, RN-2 and RN-3. The RNs can be located at arbitrary but known positions. For simplicity, we consider that the RNs are located at the corners of a rectangular field as shown in Fig. 1. We

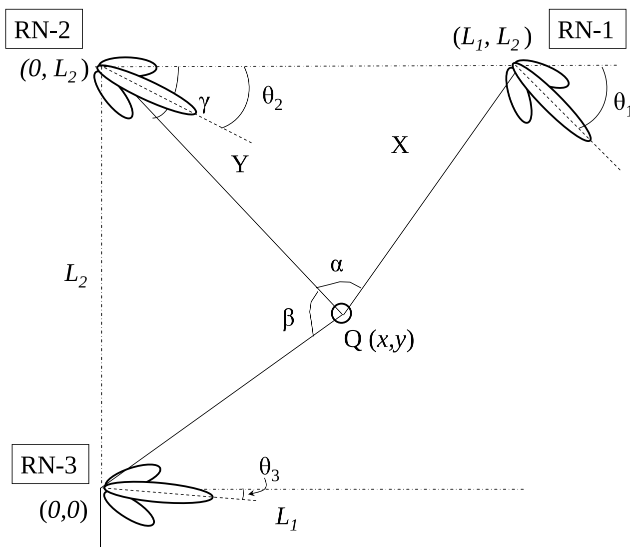

Figure 1: Arrangement of the reference nodes and the coordinate system

further assume that the origin is at RN-3. Now, consider the situation where a mobile node Q joins the network and needs to determine its coordinates (x,y) with respect to the RNs.

In this paper, we present a directional beacon based algorithm which will allow the mobile node Q to determine its coordinates. This algorithm requires each RN to be equipped with a rotating directional antenna, the hardware implementation of which is discussed in Section 4. The localization principle is based on observing the times when node Q receives the different beacon signals, and evaluating its angular bearings and location with respect to the RNs by triangulation [3, 4]. It is necessary that the transmissions from different RNs are distinguishable at Q. This may be achieved for example by using different frequencies or stamps or coded sequence of pulses for each beacon.

If the times at which Q receives beacons from RN-1, RN-2 and RN-3 are t_1, t_2 and t_3, respectively, the bearings of Q (refer to Fig. 1) can be obtained as:

$$\begin{aligned} \alpha &= \phi_1 - \omega(t_2 - t_1) \\ \beta &= \phi_2 - \omega(t_3 - t_2) \end{aligned} \tag{1}$$

where ω is the angular speed of the rotating directional beam in degrees/s, and ϕ_1 and ϕ_2 are the constant angular separation between the directional beams of the RNs. Note that $\phi_1 = \theta_1 - \theta_2$ and $\phi_2 = \theta_2 - \theta_3$. RN-$i$ broadcasts its initial angle θ_i at start of rotation. From (1) it is clear that absolute timings are not required as we are dealing with time differences in calculating the bearings.

We make use of the geometry of the RNs to obtain (x,y). Using simple trigonometry, it can be shown that the coordinates (x,y) of the node Q are given by [8]

$$\begin{aligned} x &= \frac{L_2 \cos\gamma}{\sin\beta} \cos(\beta - \gamma) \\ y &= \frac{L_2 \cos\gamma}{\sin\beta} \sin(\beta - \gamma) \end{aligned} \tag{2}$$

where

$$\gamma = \tan^{-1}\left(\frac{L_2 \cot\beta - L_1}{L_1 \cot\alpha - L_2}\right)$$

The symmetric arrangement of the RNs in Fig. 1 leads to a simple relation in (2). However, the localization principle in (2) is valid for any arrangement of the RNs.

3. DIRECTIONAL BEACON-BASED POSITION LOCATION ALGORITHM

Directional beacon based position location algorithm requires detection of the LOS component to mark the time instant when the transmitting beam is aligned with the receiver. Different approaches can be used to detect the LOS component, for instance, the scheme in [4] searches for the maximum of the received signal strength in order to mark the times. Due to the very nature of indoor multipath propagation environment, the received signal consists of signal copies due to reflection and scattering as well as the direct LOS component. We rely on the earliest signal component (instead of the strongest component) to detect the LOS component. This works well for both clear LOS and obstructed LOS scenarios.

The algorithm details for the system in Fig. 1 are as follows:

Step 1. Reference node RN-1 will transmit a signal continuously while its antenna is being rotated at a constant angular speed (ω).

Step 2. The received signal at the mobile node will consist of multiple copies of the transmit signal due to multipath propagation. Store the received signal samples for further analysis.

Step 3. Estimate the amplitude profile of the received signal at the mobile node (Section 5). The received signal amplitude profile, $y(\varphi)$, can be modeled as:

$$y(\varphi) = \sum_{m=1}^{M} a_m s(\varphi - \psi_m) + \eta(\varphi)$$

where $s(\varphi)$ is the expected amplitude profile based on the beam pattern of the directional antenna as a function of the angle φ, M is the number of signal components received at the mobile node including the LOS component and ψ_m are the phase shifts of the signal components.

Step 4. Estimate the time shift (t_1) associated with the LOS signal component in $y(\varphi)$ due to RN-1 (Section 5.2).

Step 5. Repeat steps 1-4 for RN-2 and RN-3 to obtain t_2 and t_3, respectively. Finally, use (1) and (2) to obtain the coordinates of node Q .

4. PROTOTYPE IMPLEMENTATION

Our implementation is based on a software defined radio (SDR) platform. The SDR set-up allows us the ease and flexibility to design transceiver with user controlled parameters. The rotating beacons are generated using a directional antenna coupled to a stepper motor. We describe the details in the following subsections. Fig. 2 illustrates the block level set-up at the transmitting RN.

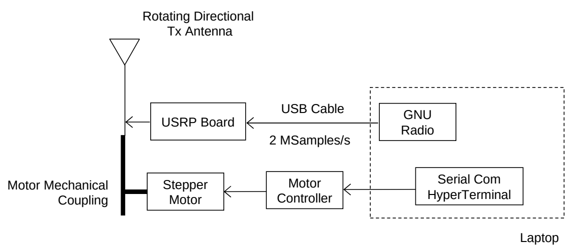

Figure 2: Hardware setup for the transmitter with rotating directional antenna

4.1 Hardware and Software Platform

For the RF front end of the software radio, we use the Universal Software Radio Peripheral (USRP) boards from Ettus Research [11]. It consists of a daughter board (RFX2400), capable of transmitting and receiving RF signals in 2.4-2.5 GHz band. The USRP also contains four analog-to-digital converters (ADCs) each with 12-bit resolution sampling at 64MS/s. Similarly, there are four 14-bit digital-to-analog converters (DACs) each operating at 128MS/s.

The rotating beacons are generated by mounting a directional antenna over a stepper motor. Each stepper motor has its own driving circuitry that is independent of others. The directional antenna consists of a 16 element linear antenna array from Telex and has a main lobe beamwidth of 30°. We use a bipolar stepper motor, 8718L-02S, from Lin Engineering which allows us to rotate the antenna with a constant angular speed. For the experiments we set the motor to rotate the antenna at 0.47 rpm.

The software radio is implemented in an open public license software called GNU radio [12]. GNU radio provides a library of blocks for radio transmission and reception. These blocks are glued together using the Python scripting language.

4.2 Experimental Setup

The experiments were carried out in an indoor fieldhouse at the University of Minnesota Recreation Center. The test area was a rectangular field measuring 55.14 m by 43 m and snapshots of the experimental set-up are shown in Figs. 3(a) and 3(b). The RNs were placed at three corners of the rectangular field and the mobile node whose position is to be determined was placed inside the field.

Steps 1-4 from Section 3 are repeated for each of the RNs and samples of the received signal at node Q are stored to a data file. To keep file sizes manageable, we store only the first 32 samples out of every 6400 samples to the hard disk.

5. SIGNAL PROCESSING FOR POSITION LOCATION

Here we outline the signal processing techniques used in Steps $3-4$ of the algorithm outlined in Section 3. In the interest of space, we refer the reader to [13] for further details.

5.1 Signal Detection and Amplitude Profile Estimation

At the transmitter, we generate a baseband signal in discrete time using the GNU radio. To simplify the receiver algorithms, we generate a single tone of the form $y\sin(\omega_o n+\theta)$ where y represents the amplitude, $\omega_o \in [0,2\pi]$ is the frequency and θ is the phase. The value of ω_o is different for each RN and is used to distinguish the beacon signals from different RNs. Due to practical constraints, the data transfer over the USB interface to the USRP board is intermittent resulting in intermittent signal transmission. We model this scenario, at the receiver, as 'hypothesis' H_1 that the data is successfully transferred to the USRP board resulting in a successful transmission (and reception) and under H_0, we assume that the data transfer to the USRP failed resulting in only noise being received. As a first step we would like to detect whether a given burst of N_b samples belongs to H_1 or H_0. The maximum likelihood estimation of the amplitude y for a given data burst containing N_b samples is given by [14, pg. 195]

$$\hat{y}_{ML} = \frac{2}{N_b}\left|\sum_{n=0}^{N_b-1} r(n)e^{-j\omega_o n}\right|. \tag{3}$$

where $r(n)$ represents the samples of the received signal. We then use a threshold γ to decide between the two hypothesis such that $\hat{y}_{ML} \underset{H_1}{\overset{H_0}{\lessgtr}} \gamma$. The threshold γ is generally set to 5-10% of the maximum value of the received signal.

5.2 Estimation of the LOS Component

Now we discuss the procedure for estimating the LOS component in a multipath environment using the least squares error criterion. Let $y(\varphi)$ represent the estimated amplitude profile of a continuous time received signal, obtained using the procedure outlined in Section 5. We can write the discrete time amplitude profile of the received signal as:

$$y(n) = y(\varphi)|_{\varphi=n\omega T_s},$$

where ω is the speed of rotation of the antenna in deg/s and T_s represents the sampling time of amplitude profile signal. If $s(\varphi)$ represents the expected antenna beampattern we can model the received signal amplitude profile as

$$y(\varphi) = \sum_{m=1}^{M} a_m s(\varphi-\psi_m)+\eta(\varphi), \tag{4}$$

where M is the number of signal components (or copies) received at the receiver including the LOS component. In discrete time, the amplitude profile of the received signal can be modelled as

$$y(n) = \sum_{m=1}^{M} a_m s(n-\tau_m)+\eta(n). \tag{5}$$

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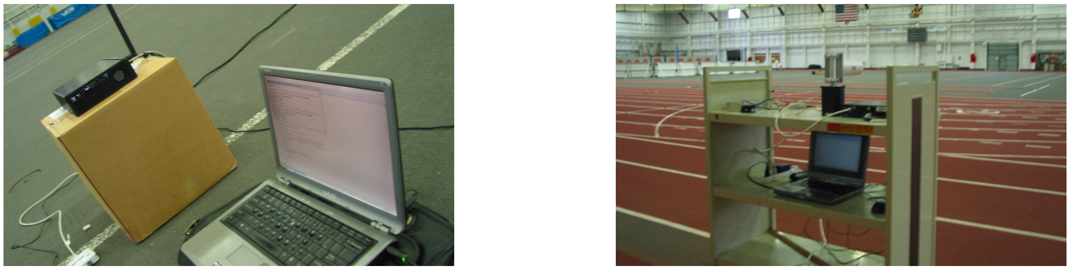

(a) The mobile node with unknown coordinates.

(b) The reference node equipped with directional antenna.

Figure 3: Experimental Setup.

Assuming we have N values of $y(n)$, in a single rotation of the antenna, that we use to estimate $\mathbf{a} = [a_1 \cdots a_M]^T$ and $\tau = [\tau_1 \cdots \tau_M]^T$, we can write (5) in matrix-vector form as

$$\mathbf{y} = \mathbf{S}(\tau)\mathbf{a} + \eta, \tag{6}$$

where $\mathbf{y} = [y(0) \cdots y(N-1)]$ and $\mathbf{S}(\tau)$ is an $N \times M$ matrix with $[\mathbf{S}(\tau)]_{n,m} = s(n - \tau_m)$. The model in (6) is linear in $\mathbf{a}$ that can be estimated using least squares (LS) solution. To solve for τ we invoke smart non-linear optimization techniques. Due to space limitations, we omit the details that are available in [13].

6. EXPERIMENTAL RESULTS

The first step in the proposed algorithm for position location is to estimate the amplitude profile of the sinusoidal signal at the received mobile node Q. A typical plot of the received signal at node Q for one 90° rotation of the transmitting antenna at RN-2 is shown in Fig. 4. We use (3) to obtain the ML

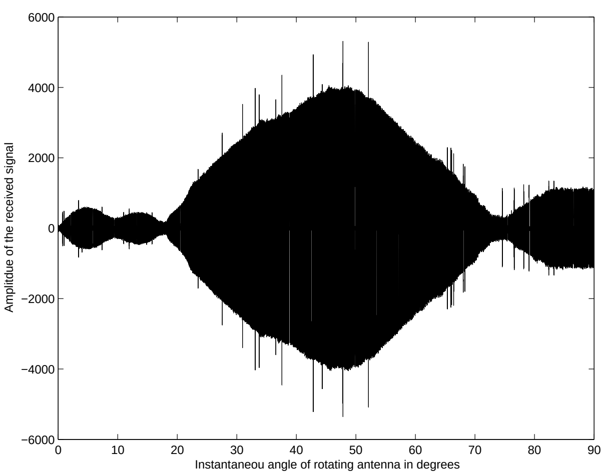

Figure 4: Received signal from 90° rotation of the RN-2

estimate of the amplitude of the sinusoid in a single burst of the received data shown in Fig. 4. The estimated amplitude profile $y(\varphi)$ for $\varphi = 0$ to 90° is shown in Fig. 5.

We use the algorithm described in Section 5.2 to estimate the LOS and multipath components in the received signal data. For simplicity, we use $M = 2$, i.e., we consider the LOS component and a single reflection or multipath component. In our experimental setup $T_s = 16\mu s$, $\omega = (90/32)$ deg/s and the amplitude profile $y(n)$ is 10,000 samples long.

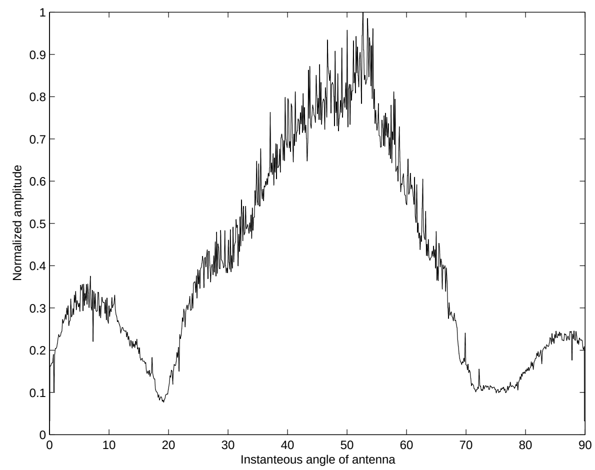

Figure 5: Amplitude profile of the received signal

In Fig. 5, we show a plot of the estimated amplitude profile $y(n)$ for the received signal from RN-3. The antenna beampattern (or radiation pattern) for the azimuth angle of 0 to 90 degrees, which represents $s(n)$, is shown in Fig. 6.

We use MATLAB optimization routines (`fminunc`) and obtain the time-delay estimate $\hat{\tau} = [\hat{\tau}_1\ \hat{\tau}_2]^T$. and the LS estimate of the complex amplitude $\hat{\mathbf{a}}_C = [\hat{a}_{C1}\ \hat{a}_{C2}]^T$ which comprises the LOS and multipath component amplitudes. For the received signal from RN-3, the estimated LOS and multipath components are shown in Fig. 7 with amplitudes $|\hat{a}_{C1}|$ and $|\hat{a}_{C2}|$, respectively. We use the earliest component (smaller of the τ_i's, $i = 1,2$) as the LOS component which is true for both clear LOS and obstructed LOS scenarios. We repeat this procedure for the received signal from other RNs to obtain the estimates for $t_i, i = 1,2,3$ in (1). The t_i's represent the location of the estimated LOS component for each RN. Finally we use (1) and (2) to estimate the position of the mobile node Q.

For further improving the position estimate, we use repeated 90° rotations of the transmitting antenna at each RN. Since this increases the data record length used for amplitude estimation, we expect the signal-to-noise ratio (SNR) to increase and the estimation error variance to decrease. In Fig. 8, we plot the variance of the position estimation error as a function of the number of 90° antenna rotations. After using data from eight 90° rotations of the antenna the root mean square position error goes down to 0.362 m.

The proposed positioning system is resilient to errors in

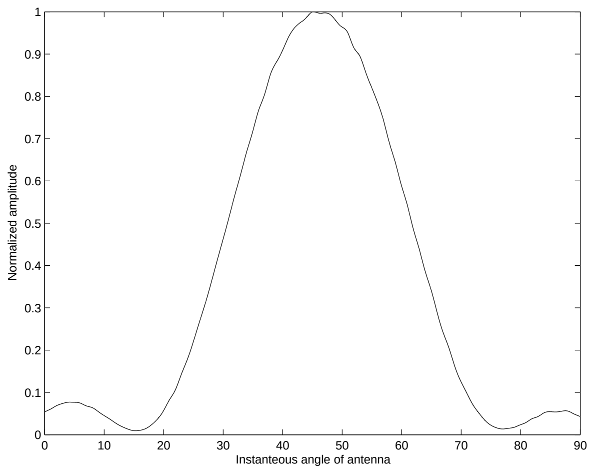

Figure 6: Antenna Beampattern (signature)

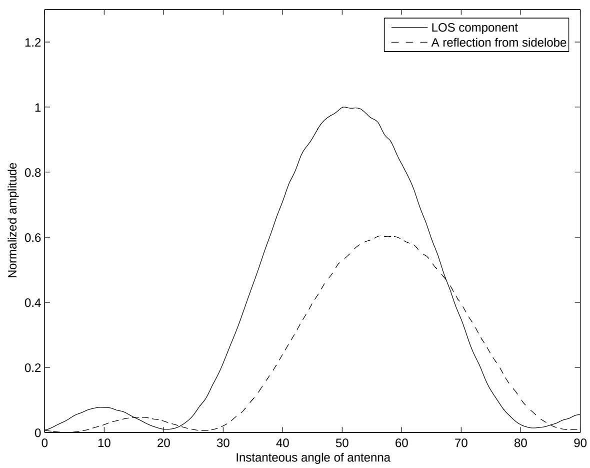

Figure 7: Estimated LOS and multipath components

time delay estimation, synchronization among RNs and motor step errors. Due to space constraints this error analysis will be presented in a future publication [15].

7. CONCLUSION

The system implementation for a directional beacon based position location algorithm using RF signals was presented. Novel techniques for improving the position estimation accuracy using maximum likelihood amplitude estimation, least squares based time-delay estimation and combining data from multiple antenna rotations, were presented. We demonstrated, through experiments, the ability to obtain position estimation results with sub-meter accuracy.

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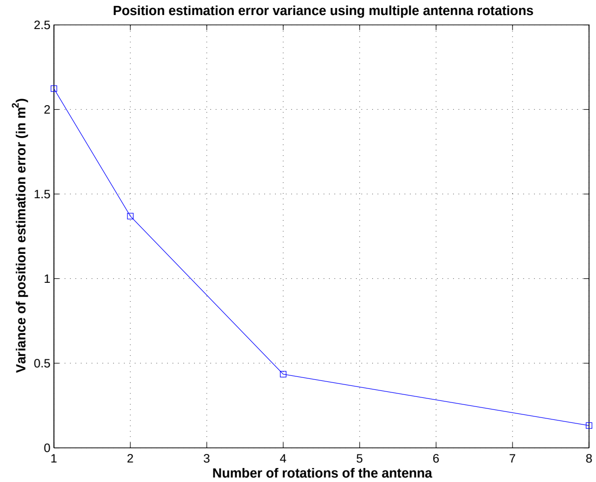

Figure 8: Position estimation error variance as a function of the number of rotations of the antenna

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