InPhase: An Indoor Localization System based on Phase Difference Measurements

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***Abstract*—Localization is an important challenge for all applications with autonomous navigating devices. Systems like GPS solve this challenge for most outdoor applications but such systems are not able to operate indoors. Indoor localization therefore is an active research topic. When it comes to locating nodes that travel from indoors to outdoors most systems are overwhelmed. Thus, we propose a system capable to localize nodes in such applications by using COTS transceiver chips. We utilize the phase measurement unit to perform distance measurements.**

I. INTRODUCTION

For highly automated cars it is crucial to know their own position to be able to navigate. In normal outdoor conditions the challenges of localization are solved by systems like Global Positioning System (GPS). Thinking of indoor and mixed environments like parking garages, most of the challenges are not satisfactorily solved by now. Of course, the use cases for such localization techniques are not limited to automotive applications. For example, logistics applications and industrial-used mobile robots also need such information.

In all these applications the localization is supposed to be as low cost as possible by retaining the accuracy. Therefore, most devices have resource constraints, which make localization of nodes a challenging task. Due to these constrains complex measurements like Time Difference of Arrival (TDoA) are not possible as only a single transceiver is available. As described by Boukerche et al. [1] different transmission channels like a radio pulse and a ultrasonic pulse are needed to realize this kind of TDoA measurements. TDoA measurements can also be realized using multiple transceivers for the same channel at different locations which results in rather large devices. Some transceivers support Time of Arrival (ToA) measurements but using this for ranging is complicated as a highly synchronized clock between the nodes is needed.

We propose an indoor localization system that fulfills the special requirements for resource constrained devices. It is capable to work with COTS transceiver chips like the AT86RF233 [2] by Atmel. Due to its measurement range, it can be used in both, indoor and outdoor scenarios. Therefore, it is capable to cover mixed application scenarios where nodes travel from indoors to outdoors and vice versa.

The remainder of this paper is structured as follows. In the next section we describe existing approaches to identify the advantages and disadvantages. Afterwards we give an overview of our proposed system and its inner workings to measure the distance between two nodes. Section IV investigates the challenges of estimating a position from the measured distances. Finally, we present the setup for a competition we participate in and also some lessons learned.

II. RELATED WORK

Several methods for distance measurements have been proposed. Many applications typically use one of these approaches: Received Signal Strength Indicator (RSSI)-based, time-based or phase-based measurements. In this section, we will briefly introduce them.

A. RSSI

Basically, the strength of a radio signal decreases with the distance between transmitter and receiver. The remaining received power might be an indicator for the distance. In real world scenarios, this simple approach does not work well due to reflections which result in constructive or destructive interference. Even in outdoor scenarios with a direct line of sight between transmitter and receiver, these reflections occur, e.g. on the ground.

Although it is hard to calculate the distance to a single transmitter only based on the RSSI, so called fingerprinting can be applied which leads to reasonable results. If the RSSI of beacons from multiple fixed stations like WLAN access points can be received at the same time, these values can be stored in a central database. Later the node which needs to know its position, submits RSSI values of its neighbors to the database which answers with the position. Changes in the environment (disappearing stations, ...) lead to inaccurate positions, even moving object like cars will have an influence.

B. Time

Every radio signal transmitted travels with the (medium-specific) speed of light through space which means that the propagation time can also be used as an indicator for the distance. For this, two variants have to be distinguished, Time of Arrival (ToA) and Time Difference of Arrival (TDoA) [3]. If both, the transmitter and the receiver have highly synchronized clocks, the signal's time of flight can be calculated if the receiver knows the exact time when the signal was sent. The latter method, TDoA, measures either the ToA between multiple receiving nodes or at one single node the ToA of signals with different propagation speeds, like ultrasound and radio waves [4]. The Global Positioning System (GPS) run by the United States government is another example using the TDoA method. In this case, the receiving node uses the different transit times of signals from satellites with a known

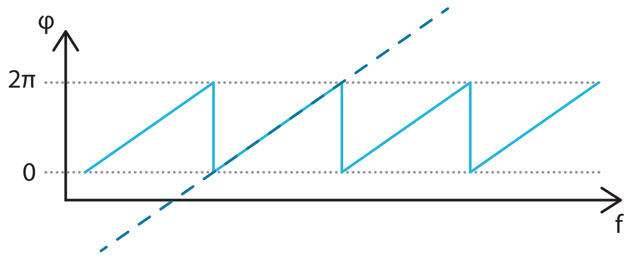

Fig. 1. Ideal phase response from PMU used for distance calculation. The indicated slope is proportional to the distance between the nodes.

position. For civil use, the accuracy of the position is about 15 m. To improve the performance of the system, Differential Global Positioning System (DGPS) can be used. In this case, an additional base station with a known position transmits the error of the position usually via a local short range radio links.

C. Phase

In the near field, the magnetic and electrical field components of electromagnetic transmitters are not in phase [5]. If a receiver is able to measure both components of a signal individually, the wavelength can be used to calculate the distance between sender and receiver. Large wavelengths are needed for precise measurements which result in huge antennas which may be a problem for small sensor nodes.

Another option is to measure the phase difference of signals with two signals between a transmitter and receiver. If it is possible to transmit or receive at two frequencies at the same time, no synchronization of clocks is required [6].

It is also possible to measure the phase difference of signals sent sequentially [7]. No absolute synchronization between transmitter and receiver is needed. Depending on the frequency offset, either high ranges or a high accuracy can be achieved with these measurements.

The approach shown in this paper uses the same method, but we use more measurement steps and apply calculations on the data which leads to a good result of the phase measurements for distance estimation.

III. DISTANCE MEASUREMENT

Our system consists of multiple INGA [8] sensor nodes forming a Wireless Sensor Network (WSN). The sensor nodes are equipped with an AT86RF233 [2]. This is an IEEE 802.15.4 compliant transceiver chip that features a PMU.

We have implemented the Active Reflector (AR) method as proposed by Kluge and Eggert [9] as distance sensor for the Contiki operating system [10]. The AR method uses two wireless sensor nodes to measure the phases of a transmitted continuous wave signal between them.

For an AR measurement two nodes are needed. In our setup we use an *anchor* and a *tag*. In the first step the *anchor* acts as receiver and measures the phase of the signal transmitted by the *tag*. To mitigate the effect of unsynchronized clocks both nodes switch roles after the first measurement. Therefore, in the second step the *tag* measures the phase of the signal transmitted by the *anchor*. As both transceiver's Phase Locked Loops (PLLs) run at the same frequency in transmission and reception mode, any phase difference due to not synchronized clocks is irrelevant.

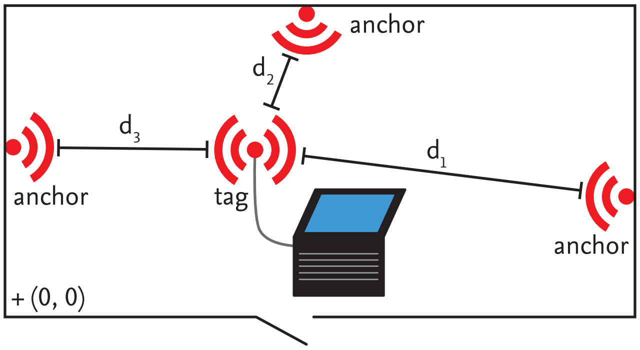

Fig. 2. Example deployment of our system in a sample room. Three fixed nodes are used as *anchors*. A fourth *tag* is connected to a portable computer.

A schematic plot of such a measurement is shown in Figure 1. The dashed blue line represents the slope of the phase response (solid blue line) of the channel measured by the system. This slope is proportional to the distance between the nodes. To start a measurement, we designed a protocol where the *tag* asks an *anchor* to participate in a measurement of the channel's phase response. After the measurement is completed, the results stored at the *anchor* are transmitted to the *tag*. This phase measurement is repeated with different *anchors* deployed at known positions.

By estimating the similarity of the measured phase response with an ideal saw tooth signal our system calculates a Distance Quality Factor (DQF). This DQF is used to decide whether the measurement should be used for position calculation or if it is not good enough.

IV. POSITION ESTIMATION

After performing distance measurements to multiple *anchors*, the position of the *tag* is computed. We employ a heuristic solver based on Sequential Least Squares Programming [11] for this task. This solver tries to minimize an error function for the *tag's* position. The bounding box of the area where the system is deployed and a starting position for the optimization is used as input for the solver. This starting position is either the last position of the *tag* if the optimization was successful or a generic starting point otherwise. The error function takes the measured distances d_n, the known positions of the *anchors* and the designated *tag's* position from the solver as input. From this input the distances between *tag* and *anchors* are calculated. Then, the relative errors to the measured distances d_n are calculated. The error function does not use all measured distances and *anchors* but only the ones with the best quality as indicated by the DQF. The sum of these errors is returned to the solver for further optimization. The solver evaluates the error function multiple times to find a local minimum of the error function. When the optimization is completed and successful, the calculated position of the *tag* is returned. This position can then be displayed to a user or used for other purposes.

V. COMPETITION

With our system we participate in the *Microsoft Indoor Localization Competition* at the *IPSN 2015*. Figure 2 shows the minimal deployment our system needs to be able to work. The competition area has of course a more complex shape and also includes multiple rooms. Depending on the size and layout of the area to cover at least three *anchors* are needed. As permitted by the competition's rules, we will deploy ten *anchors* over the whole area. Our *anchors* are mounted to the walls of the setup area. The position of the *anchors* must be measured as exactly as possible to ensure an accurate localization of the *tag*.

The *anchors* are placed carefully to ensure maximum coverage of the area. For valid measurements a direct line of sight between the *anchors* and the *tag* is required. The availability of the line of sight is critical as measurements through objects other than air will result in distance errors. Due to the directional antenna design of the INGA sensor node it is crucial that the predominant directions of the antennas are pointing at each other. To mitigate this requirement the tag features an omnidirectional antenna. This allows arbitrary placement of the tag without the requirement to align it to the anchors. However, the anchor's antennas must still point at the tag to ensure a valid measurement. All sensor nodes are placed at the same height to further reduce the effect of the directional antennas.

The *tag* is connected to a portable computer. The measurement data is sent to this device where the position is calculated and the result is displayed.

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