A Passive Source Localization System for IEEE 802.15.4 Signal

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***Abstract*—In this work, we provide a passive location monitoring system for IEEE 802.15.4 signal emitters. The system adopts software defined radio techniques to passively overhear IEEE 802.15.4 packets and to extract power information from baseband signals. In our system, we provide a new model based on the nonlinear regression for ranging. After obtaining distance information, a Weighted Centroid (WC) algorithm is adopted to locate users. In WC, each weight is inversely proportional to the nth power of propagation distance, and the degree n is obtained from some initial measurements. We evaluate our system in a $16m * 18m$ area with complex indoor propagation conditions. We are able to achieve a median error of $2.1m$ with only 4 anchor nodes.**

I. INTRODUCTION

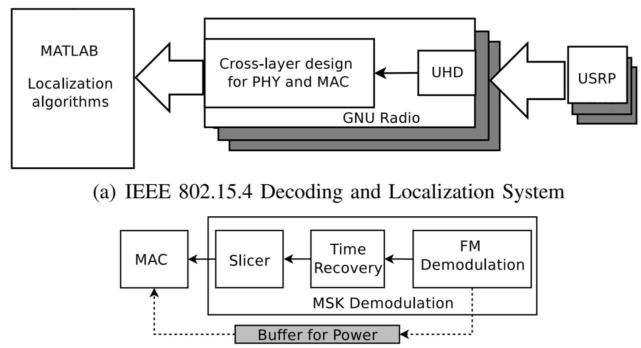
In the last years, research on the topic of indoor localization has become increasingly important, motivated by the attractiveness of business cases in various application fields such as home automation and security. IEEE 802.15.4 is a wireless standard for short-range communication, and widely used in wireless sensor networks and industry applications. It has attracted interests as a solution for indoor localization [1].

Our system contributes to the field of passive source localization, in which an important characteristic is that no localization support functionality is on the target. Anchor Nodes (ANs) just overhear the packets from the target. In practice, the system can provide location information to third-party providers of positioning and monitoring services. In addition, the system can be used to design and evaluate novel positioning algorithms.

We adopt a weighted centroid algorithm to localize the target because of its robustness to noise and simplicity. WC calculates the position of the target as a weighted average of the AN coordinates [1]. Each weight is inversely proportional to the nth power of propagation distance. Therefore, the first step in WC is to calculate the propagation distances based on received power information. The Log-normal Distance Path Loss (LDPL) model is typically adopted to map the power information (P_r) into propagation distance d [1]:

$$P_r = P_t - (\mathrm{PL}(d_0) + 10 \cdot \beta \cdot log_{10}(\frac{d}{d_0}) + X_\theta). \qquad (1)$$

P_t is the transmission power in dBm, $\mathrm{PL}(d_0)$ is the path loss at reference point d_0, and β is the path loss exponent. X_θ is a zero-mean normal random variable reflecting shadowing attenuation in dB. Because shadowing attenuation is a random variable and challenging to be modelled in different environments, non-line of sight propagation would introduce a large ranging error to the LDPL model. In addition, multipath



(a) IEEE 802.15.4 Decoding and Localization System

(b) Cross-layer Design for PHY and MAC Block

Fig. 1: The Structure of IEEE 802.15.4 Localization System

propagation will introduce some constructive and destructive interference to power, which makes high accurate ranging with the LDPL model more challenging.

In our system, the first novelty is that we model the relationship between the power and propagation distance as a curve fitting problem instead of LDPL. A nonlinear regression method is adopted for ranging. Second, in order to achieve high localization accuracy, we propose to calibrate the degree of n to find the optimal value based on some initial measurements. In addition, to our knowledge, we are the first to provide a passive source localization system based on software defined radio techniques for IEEE 802.15.4 signals, in which the target can be localized in real time and does not need to participate into the localization process.

II. A PASSIVE IEEE 802.15.4 LOCALIZATION SYSTEM

As shown in Figure 1(a), the system comprises three main components, i.e., Universal Software Radio Peripheral (USRP) for signal capturing, GNU Radio for signal processing, and MATLAB for localization algorithms.

We implement a cross-layer structure integrating physical and Media Access Control (MAC) layers into one GNU Radio block [2], which can efficiently pass the parameters from physical layer to MAC layer. Figure 1(b) indicates the cross-layer structure in GNU Radio, where we implement the same Minimum Shift Keying (MSK) demodulation scheme as [3] at the physical layer. The baseband power for each sample is obtained before Frequency Modulation (FM) demodulation. Before a packet is reconstructed, the power for each sample needs to be stored in a buffer. As soon as the packet is reconstructed at the MAC layer, the power for this packet is obtained by averaging all the samples in the packet.

III. Weighted Centroid Algorithm with NLR

In our IEEE 802.15.4 localization system, we adopt a WC algorithm including two steps, ranging and localization.

A. Ranging

As mentioned in Section I, the LDPL model has been demonstrated to be an inaccurate model in indoor environments. In our work, we propose to model the relationship between the power values and propagation distances as a nonlinear curve fitting problem. Hence, we provide a nonlinear regression (NLR) model as,

$$d = \alpha \cdot e^{\beta \cdot P_r} \tag{2}$$

where d is the propagation distance, P_r is the received power, α and β are two unknown parameters in the model that need to be obtained from some initial measurements.

Given N training positions in the initial measurements, $(d_j, P_{r,j})$ are collected at the jth training position. We apply nonlinear least square criterion, in which the sum of squared residuals should be minimized as,

$$\underset{(\alpha,\beta)}{\operatorname{argmin}} \sum_{j=1}^{N} (\alpha \cdot e^{\beta \cdot P_{r,j}} - d_j)^2. \tag{3}$$

To find the solution of this unconstrained optimization problem, the trust region algorithm [4] is applied, because it is robust and has strong global convergence property.

B. Weighted Centroid Algorithm for Localization

After distance information is obtained, the location $(\hat{x}, \hat{y})$ of the target can be estimated as,

$$(\hat{x}, \hat{y}) = \sum_{i=1}^{N} \frac{w_i}{\sum_{j=1}^{N} w_j} (x_i, y_i), \tag{4}$$

where (x_i, y_i) are the coordinates of the ith AN, N is the number of ANs and w_i is the weight for the ith AN. Each w_i can be calculated as,

$$w_i = \frac{1}{d_i^n} \tag{5}$$

where n is the nth power of the distance. With the LDPL model, the degree of n is supposed to be between 1 and 1.8 in [1]. With the NLR model, we need to reevaluate the optimal value for n. In our work, we propose to calibrate the degree of n to achieve the minimal localization error based on the initial training positions, and the calibrated n would be adopted in the localization tests.

IV. Measurements Results

We tested our system on the third floor of the IAM building in the University of Bern. First, in order to obtain the the α and β in NLR and n in Equation (5), we conduct some initial measurements at 9 positions in our target area. Then, the localization testing measurements are conducted at 53 positions in as shown in Figure 2 .

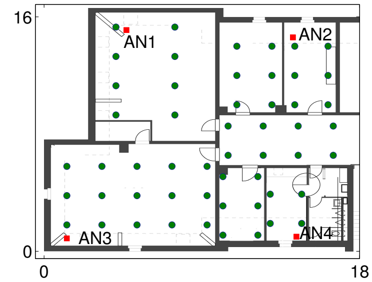
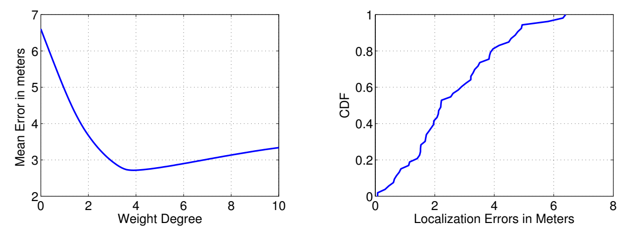


Fig. 2: Measurements Setup

Based on the initial measurements, we obtain the α and β ($\alpha = 3.082$ and $\beta = -0.0281$) in the NLR model. After that, we search n in Equation (5) from 0 to 10 at steps of 0.1 to find the optimal n, which can achieve the smallest localization error for the training positions. As shown in Figure 3(a), the mean error is minimal when $n = 3.9$.

Figure 3(b) shows the Cumulative Distribution Function (CDF) of the localization errors in the localization measurements at the 53 test positions. According to the results, the median error achieves $2.1m$ and 80% of the errors are smaller than $4m$.



(a) Mean Error with Different Weight Degree in the Initial Measurements

(b) Localization Error in the Localization Measurements

Fig. 3: Measurement results

V. Conclusions

We provide a software defined radio based passive localization system for IEEE 802.15.4 signals, in which we use power information of baseband signal instead of the RSSI in the MAC layer for localization. We adopt a nonlinear regression method to map the power information to distance information. After obtaining the NLR model in some initial measurements, we are able to achieve a median error of $2.1m$ based on a weighted centroid algorithm in a $16m * 18m$ area with only 4 receivers.

References

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