# RoSense: Refining LOS Signal Phase for Robust RFID Sensing via Spinning Antenna

Yinan Zhu[1], Chunhui Duan[2], Xuan Ding[1]
[1]School of Software and BNRist, Tsinghua University, Beijing, China
[2]School of Computer Science and Technology, Beijing Institute of Technology, Beijing, China

## ABSTRACT

RFID sensing leveraging backscatter signal features (*e.g.*, phase shift) from tags has gained increasing popularity in numerous applications, but also suffers from negative impacts of environmental multipaths. Past works to address it rely on extra customized devices, labor-intensive offline training or frequency channel hopping, all of which are non-ubiquitous or ineffective for real-life adoption. This paper presents *RoSense*, a universal method to alleviate multipath reflections' impacts by spinning the reader antenna, thus enabling more robust RFID sensing. Besides, RoSense requires no RF devices or offline training, and operates in a non-intrusive manner. The key insight of RoSense is to exploit two properties of line-of-sight (LOS) signal when spinning the antenna, *i.e.*, the *linearity of phase changes* and *stability of received signal strength* to attenuate the non-linear and non-monotonic effect of multipath signals and refine the phase shift of LOS signal. We have implemented a prototype of RoSense with COTS devices and studied two cases for evaluation: material identification and object localization. Experimental results show that RoSense can improve the material identification accuracy by 16.22% and reduce the mean localization error by 39.93%, greatly outperforming the state-of-the-art solutions.

## Keywords

RFID sensing, environmental multipaths, antenna spinning, LOS signal phase refinement

## 1. INTRODUCTION

Beyond identification function, RFID technology has shown its potential as battery-free, low-cost and small-sized sensors to enable ubiquitous sensing applications, such as object localization and tracking [1], material classification [4], items ordering, temperature and moisture measurement. The underlining rationale of these systems is generally leveraging the changes of backscatter signal features, typically *received signal strength* (RSS) and *phase shift* affected by targeted objects or events to retrodict them. Due to the low resolution of coarse-grained RSS measurement, phase shift is much more frequently harnessed for sensing. However, multipath effect mainly induced by environmental reflections from obstacles has always been a critical problem that limits the robustness of existing RFID sensing systems [3]. The phase readings of line-of-sight (LOS) signal are easily affected by these reflected multipath signals, yielding low accuracies and large errors of sensing results.

**Prior art.** Most works to address this problem require either extra customized RF devices (*e.g.*, software defined radios) for physical-layer signal processing, which is incompatible with existing RFID infrastructure and incurs high deployment, operation and maintenance overhead, or offline training to learn multipath profiles, which is time-consuming with a significant amount of human effort and always not cross-domain with little transferability to a new environment. The state-of-the-art work CPIX [2] is the only universal approach that exploits frequency channel hopping to cleanse signal phase. Nevertheless, CPIX still has a lot of limitations, *e.g.*, limited and unstable accuracy improvement, high time delay, and also incapability when the tag's impedance changes irregularly. To the best of our knowledge, such a ubiquitous solution which could effectively defend against multipaths still does not exist.

**Contributions.** In this paper, we present a more universal and effective method, namely *RoSense* that refines LOS signal phase via spinning the reader antenna. Moreover, RoSense requires no extra RF devices or offline training and operates in a non-intrusive manner. The basic idea is that the phase readings of LOS signal shall linearly change with the spinning angles ideally in a multipath-free environment, but slightly deviate from linear trends in a multipath-prevalent environment because the effect of multipath signals changes non-linearly and non-monotonically. Similarly, RSS readings shall remain unchanged ideally when spinning, but fluctuate within a small range due to multipaths. Accordingly, we can exploit the *linearity of phase changes* and *stability of RSS* to jointly refine the LOS signal phase via optimization algorithms. First, we conduct weighted linear regression on the collected phase vector after spinning. Then we exploit the corresponding RSS vector to calibrate the possible intercept drift in linear regression. After calibration, the refined phase is obtained. In this way, many existing sensing systems can harvest benefits, if only RoSense acts as middleware and the refined phase readings after processing are inputted to these systems. To evaluate RoSense, we study two applications: non-intrusive material identification and anchor-free object localization. Experimental results demonstrate that RoSense can achieve around 16.22% improvement of material identification accuracy and 17.52%∼39.93% reduction of localization error, which significantly outperforms CPIX.

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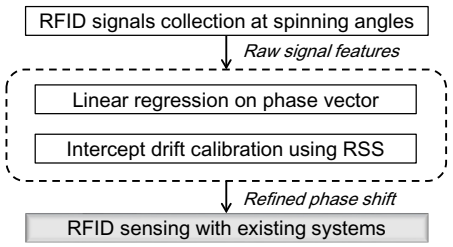



**Figure 1: System design of RoSense**

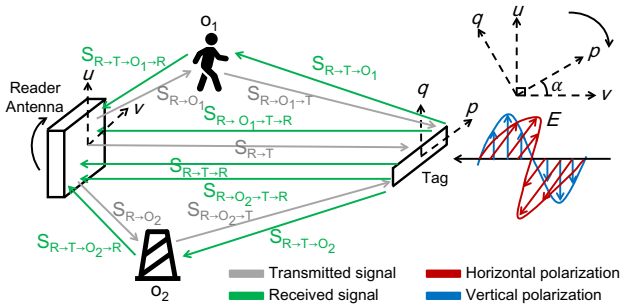



**Figure 2: Propagation of RFID signals**

## 2. SYSTEM DESIGN

Fig. 1 illustrates the system overview and RoSense contains two steps: phase vector regression and intercept drift calibration. We introduce the technical details as follows.

### 2.1 Mechanism of RoSense

Fig. 2 shows the practical propagation of RFID signals and we first analyze the tag's LOS backscatter signal received by reader (denoted by $S_{R\to T\to R}$). The total phase shift of $S_{R\to T\to R}$ is $\phi = 2\phi_d + \phi_R + \phi_T + 2\alpha$ where $\phi_R$ and $\phi_T$ denote the phase shifts induced by reader and tag hardware respectively. $\phi_R$ refers to reader-tag distance. $f$ is the communication frequency and $\alpha$ is the intersection angle between two polarized directions $v$ and $p$.

We can get two properties of $S_{R\to T\to R}$ if we spin the reader antenna around its centre in a fixed spinning plane, .

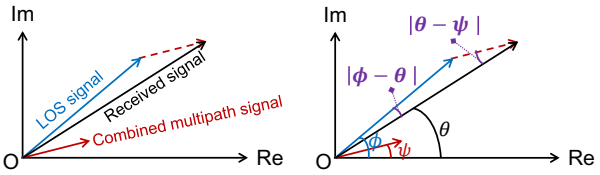
- **The linearity of phase changes.** When spinning the reader antenna uniformly, the intersection angle $\alpha$ and thus the phase shift $\phi$ would change linearly.
- **The stability of RSS.** The amplitude of LOS signal should not change with $\alpha$. Hence, the RSS would remain stable when spinning the antenna.

Next, we consider the practical effects of multipath signals (*e.g.*, $S_{R\to T\to O_1\to R}$) reflected by surrounding obstacles. The combination of multipath signals can be approximated as

$$S_M(t) \approx \sum_{i=1}^{N} 2\sqrt{p^2+q^2}\eta_i \cos(\beta_i-\alpha)\cos(2\pi f t - \delta_i) \quad (1)$$

where $\delta_i = 2\phi_{RO_iTR}+\phi_R+\phi_T+\phi_{O_i}+\alpha+\beta_i$. $\eta_i$ is the attenuation coefficient of obstacle $O_i$ and $\beta_i$ is the intersection angle between main direction of $O_i$ and $p$. $\phi_{RO_iTR}$ and $\phi_{O_i}$ refer to the phase shifts induced by the distance of $i$-th propagation path and reflection of $O_i$ respectively. The signals after multi-reflections can be negligible due to the large amplitude attenuation, as compared to LOS signal.

The RSS and phase readings reported by a commercial reader (denoted by $P$ and $\theta$) are collected from the superposition of LOS signal and combined multipath signal (see Fig. 3(b)). So we can obtain the following relationships.




(a) Superposition of signals (b) Phases' relationship

**Figure 3: Multipath effect on LOS signal**

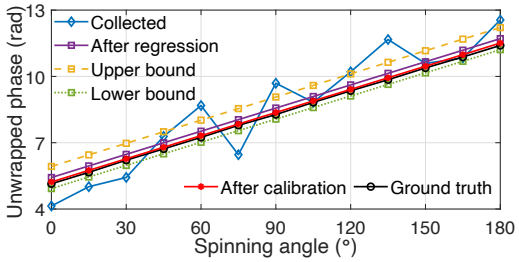



**Figure 4: LOS signal phase refinement**

$$|\phi-\theta| = \arcsin\left(\sqrt{\frac{P_M}{P}}\sin|\phi-\psi|\right) \quad (2)$$

$$\sqrt{\frac{P_{LOS}}{P}} = \frac{\sin(\theta-\psi)}{\sin(\phi-\psi)} \quad (3)$$

Here $P_{LOS}$ and $P_M$ denote the RSS of LOS signal and multipath signal respectively, $\psi$ denotes the combined multipath signal phase. We can prove that $|\phi-\theta|$ would change nonlinearly and non-monotonically when spinning the antenna. Further, $\sin(\theta-\psi)/\sin(\phi-\psi)$ would also fluctuate within a small range around 1, incurring the instability of $P$. Therefore, we can spin the reader antenna and exploit our proposed two properties of LOS signal to alleviate multipath reflections' impacts and refine $\phi$.

### 2.2 Phase Vector Regression

After antenna spinning with a step of $\Delta\alpha$ and phase unwrapping based on the monotonicity, we can obtain a vector of average phases $\Theta = \{\hat{\theta}_1, \hat{\theta}_2, ..., \hat{\theta}_M\}$, where $\hat{\theta}_k$ is the average phase at the $k$-th spinning angle and $M$ is spinning angles' quantity. Then we utilize the linear regression method to fit $\Theta$ into a line, whose gradient is a known constant $2\Delta\alpha$:

$$b^* = \arg\min_b \sum_{k=1}^{M}\left(2\Delta\alpha\cdot k + b - \hat{\theta}_k\right)^2 \quad (4)$$

where $b^*$ denotes the intercept of fitting line. After the regression, we can greatly alleviate multipath effects due to the first property, whereas the obtained intercept $b^*$ may still contain some drift incurred by uncertain environmental noises. Next, we utilize RSS for further refinement.

### 2.3 Intercept Drift Calibration

After antenna spinning, we can also obtain a vector of average RSS $\Upsilon = \{\hat{P}_1, \hat{P}_2, ..., \hat{P}_M\}$. Then we consider matching the phase error with RSS error at the same angle, thereby calibrating the possible intercept drift $\Delta b$ (within an empirical threshold $\epsilon$), based on the second property. That is,

$$\Delta b^* = \arg\min_{-\varepsilon\le\Delta b\le\varepsilon}\max_{1\le k\le M}\left\{\frac{\left|2\Delta\alpha\cdot k + b^* + \Delta b - \hat{\theta}_k\right|}{\left|\hat{P}_k - \sum_{L=1}^{M}\hat{P}_L/M\right|^{\sigma}}\right\} \quad (5)$$

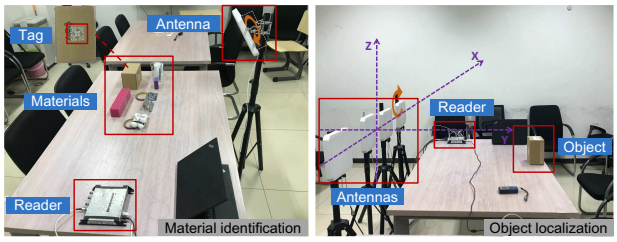
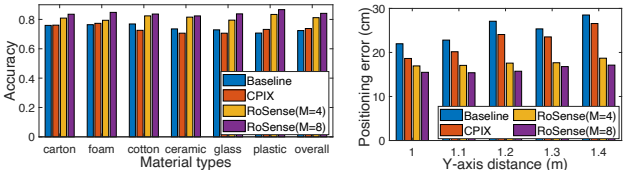



**Figure 5: Experimental setup for two sensing cases**




(a) Material identification (b) Object localization

**Figure 6: Sensing performance of two cases**

where $\sigma$ is an empirical parameter for normalization. We can transform Eq. (5) into another formulation: $\Delta b^* = \arg\min_{\Omega} \zeta$, $\Omega = \left\{\Delta b, \zeta | -\varepsilon \le \Delta b \le \varepsilon, \zeta \ge 0, -\zeta \le \frac{2\Delta\alpha\cdot k + b^* + \Delta b - \hat{\theta}_k}{(\hat{P}_k - \sum_{L=1}^{M} \hat{P}_L/M)^\sigma} \le \zeta, \forall k\right\}$ and solve it using linear programming method.

After the calibration, $2\Delta\alpha \cdot k + b^* + \Delta b^*$ is treated as the refined phase shift of LOS signal at the $k$-th spinning angle and inputted to existing RFID sensing systems. Here we illustrate an example in Fig. 4, where the ground truth of LOS signal phases is obtained in an open area with wave-absorbing material deployed, and we place some obstacles around to construct a multipath-prevalent scenario and collect the phase readings. We can find that the maximum difference between collected phase and ground truth reaches 1.820rad, but degraded to only 0.308rad after phase vector regression. By intercept drift calibration, the difference is further reduced to $\le$0.107rad. This demonstrates the potency of our method.

# 3. IMPLEMENTATION AND EVALUATION

We implement a prototype of RoSense with COTS devices and evaluate it in two cases: non-intrusive material identification using Tagtag [4] and anchor-free object localization using BackPos [1]. The employed hardware contains one ImpinJ Speedway R420 RFID reader with four antennas and Alien AZ-9662 tags, all operating at the UHF band. The reader is connected to our laptop through low level reader protocol (LLRP). The software including our algorithms for phase refinement is implemented using MATLAB. The experimental setup for two cases is shown in Fig. 5, where the ground truth of object localization is measured using a laser range finder and that of material identification is labeled in advance. At each spinning angle, we collect signal features for no more than one second. We also implement the state-of-the-art work CPIX [2] and baseline scheme (*i.e.*, using original unrefined phases as inputs) for comparison.

## 3.1 Case I (Material Identification)

We choose ten different types of materials for experiments, whereas it is hard to receive signals when tagged on metal and liquid materials, and only six types of them are applicable: carton, foam, cotton, ceramic, glass, plastic. Fig. 6(a) shows the average identification accuracy of each material. We can find that Tagtag is vulnerable to multipaths and its accuracy would drop down to 70.71%. RoSense can improve the overall accuracy by 11.74% (relatively 16.22%), greatly outperforming CPIX by 8.3×. Besides, RoSense is available for all materials and CPIX would even impair the performance in ceramic and glass cases. There are probably two reasons: the phase shift may not regularly change with frequency channels when tags are bent (*e.g.*, tagged on a glass cup); the phase cleansing procedure of CPIX is coarse without mechanism support. Among all materials, the accuracy improvement of RoSense can reach 15.96% and that of CPIX is up to 2.49%, which indicates the significant superiority of RoSense. Moreover, a larger number of spinning angles $M$ could further promote the performance to a certain degree. For instance, spinning eight angles ($\Delta\alpha = 45°$) can achieve higher accuracy than that of spinning four angles ($\Delta\alpha = 90°$) by 2.94%. This is reasonable since more angles would engender more precise regression and calibration.

## 3.2 Case II (Object Localization)

We leverage four reader antennas with known coordinates for object localization, where the Y-axis distance from antenna to tag is fixed in each experiment. BackPos is used to compute the tag's X- and Z-coordinates and obtain the positioning error. From Fig. 6(b), we can find that BackPos's mean error can be enlarged up to 28.51cm under multipaths. Our method RoSense can help reduce the positioning error to 17.12cm. As compared to CPIX, RoSense can achieve a much larger reduction of error by nearly 5.9×. Besides, RoSense maintains a fine performance under different Y-axis distances, whereas the effect of CPIX is attenuated with the increasing distance, probably due to that larger distance incurs the worse fitting error in CPIX. This also proves that RoSense can effectively work wherever the tag is located, but CPIX fails.

# 4. CONCLUSION

In this paper, we propose a novel method RoSense to refine the LOS signal phase for robust RFID sensing, by spinning the reader antenna. Experimental results demonstrate that RoSense can achieve a remarkable performance gain for two typical sensing applications and outperform the state-of-the-art works.

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