Software-Controlled Polarization for Longer-Range RFID Reading and Localization

Laura Dodds[1], Nazish Naeem[1], Aline Eid[2], Fadel Adib[1,3]

[1] *Massachusetts Institute of Technology,* [2] *University of Michigan,* [3] *Cartesian Systems*

***Abstract*—The majority of existing RFID readers rely on circularly polarized or switched polarization antennas for powering and communicating with tags. In this paper, we argue that a new form of software-controlled polarization brings important benefits to the tasks of powering, communicating with, and localizing RFID tags. Using only two linearly polarized antennas, we demonstrate how one could generate an arbitrarily linear polarization in the same plane relying entirely on software control. We incorporate this approach into a protocol that automatically discovers RFID orientations in the environment and show how this approach increases the range (or alternatively reduces the transmit power) of RFID readers. We also demonstrate this approach in an end-to-end RFID localization application.**

***Index Terms*—Polarization, Range, Power, Localization, IoT**

I. Introduction

Enabling longer read range of RFID readers is a long-standing problem in the RFID community [1], [2]. This problem is important as it enables reading tags over wider coverage areas, under more dense piles, and across different orientations. It is also important because it can enable reducing the power consumption of RFID readers, which is particularly important for handheld battery-powered research. Past research has explored different avenues for achieving this, from tag and reader antenna design to better/broader-band matching, higher sensitivity readers, self-interference cancellation hardware, etc.

In this paper, we introduce RF-Boost, a new approach for increasing the read-range using software-controlled polarization. Since the majority of existing readers rely on switched linearly polarized (LP) or circularly polarized (CP) antennas, they suffer from polarization losses, as shown in Fig. 1. For example, a switched LP system relies on only vertical and horizontal polarizations, resulting in large polarization loss for tags near 45°. Additionally, CP antennas experience a -6dB loss regardless of the tag angle. These losses limit the effective ranges of these systems. Instead, in this work, we aim to develop a system that does not incur any meaningful polarization mismatch irrespective of the tag's orientation. Furthermore, we propose doing so using only two LP antennas, which we use to generate an LP signal at an angle that matches the tag. This allows us to minimize polarization mismatch and maximize our range. We further extend this idea beyond reading tags to also fine-grained localization.

However, translating this idea into practice is difficult since the angle of the tag is unknown apriori. To overcome this, we design this approach into an efficient discovery protocol (§IV) that allows us to power and read all tags in the environment. We demonstrate that it is not necessary to match the exact tag angle in order to benefit from software controlled polarization, and show that a system that reads at multiple discrete angles is able to produce negligible polarization loss for all tags.

Next, we show the benefits of this technique extend beyond increasing the read range to also increasing the range of localization (§V-A). By leveraging a technique known as dual-frequency excitation [3], we send two signals: one to power the tag and one to localize. By also constructing angled LP localization signals within our discovery protocol, we are able to minimize polarization loss and extend the localization range.

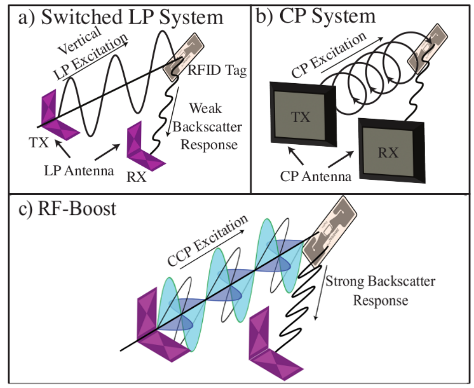


Fig. 1: **RF-Boost.** The majority of existing RFID readers leverage a) switched LP or b) CP antennas to read RFID tags, which suffer from large polarization mismatch. c) RF-Boost uses complex-controlled polarization to construct LP signals at various angles to minimize polarization loss.

Finally, to further extend the localization range, we introduce a dynamic power adaptation mechanism (§V-B). We observe that the signal-to-noise ratio (SNR) of the localization signal increases as the powering signal strength decreases. We leverage this observation by dynamically adjusting our powering signal level for maximum localization SNR.

We built a proof-of-concept prototype of our system and our empirical evaluation demonstrates that:

- In a multipath rich environment, our system increases 10th and 50th percentile SNRs by 6.3dB and 2.7dB, compared to a switched LP system with high polarization mismatch.
- Our techniques for minimizing polarization mismatch increases the localization range by almost 30%.
- Our dynamic power adaptation achieves a median of 2.7dB of SNR improvement.

II. Related Work

Polarization in RFID Readers. Polarization mismatch is a well-known phenomenon in RFIDs. Since CP signals incur a -6dB loss, prior work has investigated extending the read-range of RFID readers using linearly-polarized signals. For example, some research [4] and commercial readers [5] leverage switched polarizations (or ”dual-polarizations”), where they switch between horizontally and vertically polarized signals to avoid large polarization loss. While this approach successfully overcomes the issue of significant mismatch at near-perpendicular angles, it still results in poor performance (-6dB) at certain angles. Other research has investigated sending slant-polarization (45° LP signals) [6] instead of horizontal and vertical signals to avoid the complexity of switching. However, this makes the assumption that the majority of tags are either vertical or horizontal, which is not the case in practical environments - and RFIDs may indeed be at 135° angles and hence difficult to read with only 45° polarizations. **Polarization in RFID Localization.** Additionally, prior work [7], has investigated minimizing polarization loss for RFID localization by sending horizontal and vertical localization signals sequentially in time, and then combining the signals in post-processing to achieve improved SNR. While this work achieves higher SNR than a simple switched LP system, it requires sending two signals to accurately sense the tag, and will therefore suffer a -3dB loss at all tag angles (when normalizing the total transmit power to 1).

RF-Boost is inspired by these lines of work and builds on them by further decreasing polarization loss to increase the range of reading and localization by leveraging software-controlled polarization to construct any transmit angle. Additionally, it further improves localization range by dynamically adapting the transmitted power.

III. Primer

The majority of state-of-the-art fine-grained RFID localization relies on a technique called dual-frequency excitation [3]. This technique allows systems to perform accurate time-of-flight estimation by collecting ultra-wideband (UWB) channel measurements from narrowband COTS tags. Dual-frequency excitation leverages the fact that RFIDs are frequency agnostic, meaning that once they are powered, they reflect all incident signals. Therefore, it is possible to send two signals to an RFID simultaneously: one high-power signal (”in-band”) within the tag's bandwidth to power the tag and a second low-power signal (”out-of-band”) at a different sensing frequency outside the tag's bandwidth to estimate the channel. This is repeated at different out-of-band frequencies to measure UWB channel estimates and perform time-of-fight estimation [3], [8], [9]. RF-Boost will leverage this technique for RFID localization.

IV. Extending Read Range

In this section, we describe how RF-Boost is able to extend the RFID read range by constructing linearly polarized in-band (IB) signals at various angles to better match the tag angle.

A. Reading a Single Tag

For simplicity, we first consider the case where RF-Boost is reading a single tag. The ideal polarization in this case is an LP signal at the same angle as the tag. However, since the tag angle is unknown, it would be impractical to place a separate LP antenna at every possible angle or physically rotate an antenna to match the tag. Instead, using two LP antennas, we are able to construct any LP angle to match the tag, entirely through software control. One could vary the relative signal amplitudes between the two TX antennas [7]. We transmit:

$$TX_H = \cos(\phi)x \qquad TX_V = \sin(\phi)x \tag{1}$$

where ϕ is the desired transmit angle, TX_H and TX_V are the amplitudes of the transmitted signals on the horizontal and vertical antennas, respectively, and x is the modulated signal.

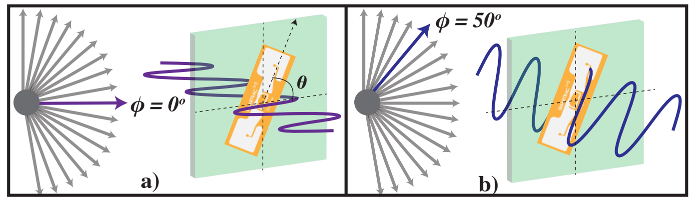


Fig. 2: **Transmit Polarization Sweep.** Two examples of transmit angles from a sweep of different angles. a) The transmitted angle has large polarization loss with the tag. b) The transmitted angle aligns well with the RFID.

Then, to receive the signal at the same angle, we project the received signals from two perpendicular antennas onto ϕ:

$$RX_{comb} = \cos(\phi)RX_H + \sin(\phi)RX_V \tag{2}$$

where RX_H and RX_V are the vertical and horizontal received signals, respectively, and RX_{comb} is the combined signal [7].

While this technique allows us to transmit at any angle, the angle of the tag is still unknown, so we cannot simply construct the ideal polarization. To overcome this, our idea is to transmit at multiple different angles sequentially (e.g., ”sweeping” the transmit angle) until the tag powers, as shown in Fig. 2. Fig. 2a shows one angle of the TX sweep, which is not well aligned with the tag angle and therefore will create large polarization mismatch, resulting in either a very low SNR or the tag not powering altogether. As the sweep continues, eventually one angle, such as the one shown in Fig. 2b, will align close to the tag and result in minimal polarization loss, and hence high SNR. While this approach may not produce a polarization at the exact tag angle, it is likely that the overall polarization loss will remain low. To see this, let us analyze the polarization loss of this scheme. Given the transmit angle ϕ and the tag angle θ, the polarization loss PL of the backscattered signal is:

$$PL(\phi, \theta) = 20\log_{10}(\cos^2(\phi - \theta)) \tag{3}$$

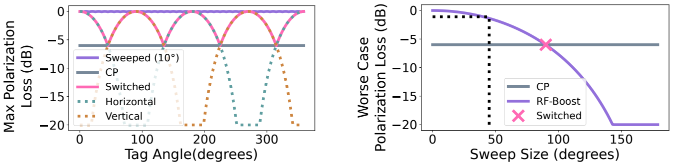
Therefore, when sweeping the TX angle, the minimum loss will occur at the TX angle nearest the tag angle. We define this minimum loss across all TX angles, PL_{min}, as:

$$PL_{min}(\Phi, \theta) = 20\log_{10}(\cos^2(\min_{\phi\in\Phi}(|\phi - \theta|))) \tag{4}$$

where Φ is the set of all transmit angles.

To compare the performance of this scheme with existing solutions, we simulated the theoretical polarization loss as a function of tag angle, shown in Fig. 3a. For a given tag angle, we simulated the loss with Eq. 4. We simulated the case where we sweep the TX angle every 10° (e.g., $\Phi = \{0, 10, ..., 350\}$), shown in purple. We compared to the performance of a fixed horizontal LP antenna($\Phi = \{0\}$), vertical antenna($\Phi = \{90\}$), and a switched LP system that switches between horizontal and vertical polarizations($\Phi = \{0, 90\}$), in green, brown, and pink, respectively. We also compared to a CP signal(gray). We clip the loss at a minimum of -20dB. We note:

- The horizontal & vertical polarizations have losses of -20dB ($-\infty$ in theory) when their polarizations are perpendicular to the tag, preventing them from reading tags across all angles.
- The switched polarization is able to read tags with 0dB loss at 0° and 90°, but shows a -6dB loss at 45°. While this scheme avoids the drastic polarization losses of simple horizontal/vertical polarizations, it would still result in limited



(a) **Polarization Loss vs Tag Angle** (b) **Worst-Case Loss vs Sweep Size**

Fig. 3: **Polarization Loss Simulations.** a) Simulation results of polarization loss when sweeping with 10° granularity(purple), switched (pink), horizontal (green), vertical (brown), and CP (gray). b) Simulation results of worst-case polarization loss vs sweep size (purple) compared to CP (gray) and switched polarization (pink x). Dotted lines denote loss at 45° granularity.

read range for a tags at certain angles.

- A circularly polarized signal has a loss of -6dB regardless of the tag angle, limiting its achievable read range at all angles.
- When sweeping with a granularity of 10°, RF-Boost reads tags with a worst-case loss of only -0.07dB (at 5°). This loss is marginal and would have minimal impact on read range.

These results show that our idea of sweeping the transmit angle will sufficiently minimize the polarization loss compared to switched, LP, or CP systems, resulting in long read ranges.

B. Extending to Multiple Tags

Next, we extend this idea to work with multiple tags. To do so, at each angle, we can perform a discovery algorithm using the EPC Gen 2 protocol, allowing us to read all the tags in the environment. However, unlike with a single tag, it is important to be efficient in the overall time required to read a large number of tags. In our system, each of our IB transmit angles that we sweep adds some additional overhead to the total time it takes to read the tags. Therefore, there exists a tradeoff between the overall discovery time and the polarization loss. For example, we can sweep with a higher granularity to achieve smaller polarization loss at the expense of additional time required to read the tags. Alternatively, we can sweep with a lower granularity to reduce the overhead, but we would incur a higher polarization loss.

To understand the impact of granularity on the polarization loss, we formalize the sweep as a function of our sweep size (e.g., number of degrees between consecutive angles) as:

$$\Phi(s) = \left\{ is \middle| i \in \left\{ 0, ..., \left\lfloor \frac{359}{s} \right\rfloor \right\} \right\} \tag{5}$$

where s is the sweep size in degrees. Given this sweep, our worst case polarization loss across any possible tag angle will occur when θ is exactly between two adjacent transmit angles (e.g. $|\phi - \theta| = \frac{s}{2}$). Therefore, the worst-case polarization loss across any possible tag angle, PL_{worst}, is:

$$PL_{worst}(s) = \min_{\theta \in [0,360]} \left(PL_{min}(\Phi(s), \theta) \right) = 20 \log_{10} \left(\cos^2 \left(\frac{s}{2} \right) \right) \tag{6}$$

Next, we simulate PL_{worst} vs. sweep size, as shown in Fig. 3b for our system (purple). We compare to a CP signal (gray), whose polarization loss is -6dB (independent of sweep size). We also denote the case of simple switched polarization with a pink x(equivalent to a sweep size of 90°). We note:

- Selecting a sweep size of 90° would result in a worst-case loss of -6dB. This shows our system is able to outperform a CP antenna across all tag angles with as few as 2 sweeps. However, operating with a 90° sweep (e.g., simple switching) still incurs a -6dB loss at some tag angles, limiting the range.
- Decreasing the sweep size from 90° to 45° (denoted by the black dotted lines) drops the polarization loss from -6dB to -1.37dB, while only requiring two additional TX angles.
- A sweep size of 22.5° results in a polarization loss of -0.33dB, requiring a total of 8 different transmit angles. This shows that beyond a sweep size of 45°, it requires 4 additional angles to decrease the polarization loss by an additional 1dB, demonstrating the diminishing returns of increased granularity.

Based on these results, we select a sweep size of 45° for our system to balance polarization loss and efficiency.

V. Extending Localization Range

In the previous section, we discussed how RF-Boost is able to extend the read range using linearly polarized IB signals at various angles. In addition read range, RF-Boost also extends its benefits to RFID localization. To localize a tag, recall from §III that we send out-of-band (OOB) signals to measure UWB channel estimates and perform time-of-flight estimation. Therefore, in order to maximize the localization range, we need to maximize the OOB SNR. In this section, we show how RF-Boost extends the localization range through two techniques: first, minimizing polarization loss ,and second, a novel dynamic power adaptation scheme.

A. Minimizing Polarization Mismatch

To maximize OOB SNR, the ideal polarization to send for the OOB signal is again a linearly polarized signal that matches the tag's angle. However, the tag's angle is still unknown. To overcome this, we sweep the OOB transmit angle at the same time and in the same way as IB, simultaneously attempting to power and localize the tag. We construct the OOB transmit and receive signals using Eqs. 1 and 2. At each angle, we transmit all OOB frequencies to attempt to measure UWB channel estimates. We then select the angle with the highest median OOB SNR across all frequencies in order to perform long-range and fine-grained localization.

This approach allows us to minimize the total loss compared to the state-of-the-art RFID localization schemes [7] (which rely only on polarization projections in post-processing). To see this, let us analyze the polarization loss of our system. Similar to our IB signals, the worst case polarization loss for our OOB sweep is given by Eq. 6. Given our selected sweep size of 45°, our worst case loss across all tag angles is -1.37dB. This shows that even in the worst case, our system outperforms the state-of-the-art's [7] loss of -3dB. Our system also outperforms a simple switched approach, which experiences a -6dB loss at certain tag angles (Fig. 3a).

B. Dynamic Power Adaptation

Next, we aim to further increase our OOB SNR and therefore localization range. To do so, we introduce a technique called dynamic power adaptation. At a high level, this technique operates based on an observation that decreasing the IB power increases the OOB SNR. To understand why

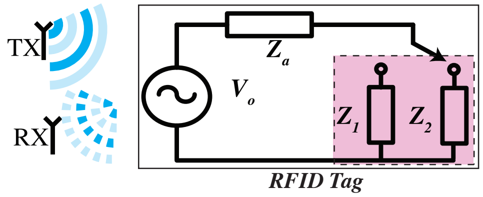


Fig. 4: **RFID Tag Circuit.** Thevenin equivalent circuit of an RFID tag showing the antenna impedance and the impedance of the two different states.

this is the case, let us first start with analyzing the theoretical backscatter power received by the system, P_r [10]:

$$P_r = P_t G_t^2 L \Delta\sigma \tag{7}$$

where P_t is the transmitted power, G_t is the gain of the transmit/receive antennas, L is the round-trip path loss, and $\Delta\sigma$ is the differential radar cross-section.

Without changing our transmit power, or antenna gain, it is possible to increase P_r by increasing $\Delta\sigma$, defined as [11]:

$$\Delta\sigma = \frac{\lambda^2 G^2}{4\pi} |\Gamma_1 - \Gamma_2|^2 \tag{8}$$

where λ is the wavelength of the transmitted frequency, G is the gain of the tag's antenna, and Γ_1, Γ_2 are the reflection coefficients of the two backscatter states. If we model the RFID tag with its equivalent Thevenin circuit as in Fig. 4, then we can define $\Gamma_{1,2}$ based on the impedance states [11]:

$$\Gamma_{1,2} = \frac{Z_{1,2} - Z_a^*}{Z_{1,2} + Z_a} \tag{9}$$

where Z_1 and Z_2 are the complex impedances of the two different RFID states, and Z_a is the antenna impedance.

Interestingly, the majority of RFIDs are built with rectifiers that are inherently non-linear and whose impedance changes with input signal power, changing Z_1 and Z_2 in Eq. 9. Since most RFID's impedance matching networks are optimized to operate at the lowest possible input power (to maximize read range), the impedance matching becomes non-ideal at higher input powers [12]. This causes a decrease in $|\Gamma_1 - \Gamma_2|$ at higher powers, and therefore a decrease in $\Delta\sigma$ and P_r.

Exploiting the Changing Impedence. We leverage this observation in our system to optimize our OOB SNR. At first, one might think that we could decrease our OOB transmit power to improve the impedance matching, increase $\Delta\sigma$, and improve our OOB SNR. However, doing so would also decrease P_T in Eq. 7, lowering the overall SNR.

Instead, we observe that Z_1 and Z_2 are determined by the overall input power to the rectifier, including both IB and OOB power. Therefore, decreasing the IB transmit power will increase the radar cross section for both IB and OOB. Since the OOB power transmitted (P_T) does not change in this case, our OOB SNR will increase due to the increased $\Delta\sigma$ (Eq. 7).

One concern with lowering IB power is that if the reader sends too low of a power, then the tag will not harvest enough energy to turn on. However, since our read-range is typically longer than localization range [7], our system is usually operating with a higher IB power than is necessary (when localizing tags). This means we can decrease the IB power while still being able to power and read the tag. Ideally, our system would transmit the minimum IB power required to power the tag, allowing us to simultaneously maximize OOB SNR. However, this ideal power level is unknown, since it is dependent on the tag distance, multipath profile, etc. To overcome this, we introduce a dynamic power adaptation algorithm that searches for the ideal IB power level to maximize the OOB SNR.

Algorithm 1 Dynamic Power Adaptation

```
function TX(φ, p)
    Transmit at angle φ with IB power p
    return IB SNR, OOB SNR, Data
// φ_m = angle selected from IB/OOB sweep
low = MIN_POWER, high = MAX_POWER, best = 0, i = 1
while low <= high do
    p_i = (low+high)/2
    IB_SNR_i, OOB_SNR_i, data_i = TX(φ_m, p_i)
    if IB_SNR_i > τ then
        high = p_i - 1
        if p_i < p_best then
            best = i
    else
        low = p_i + 1
    i = i + 1
return data_best
```

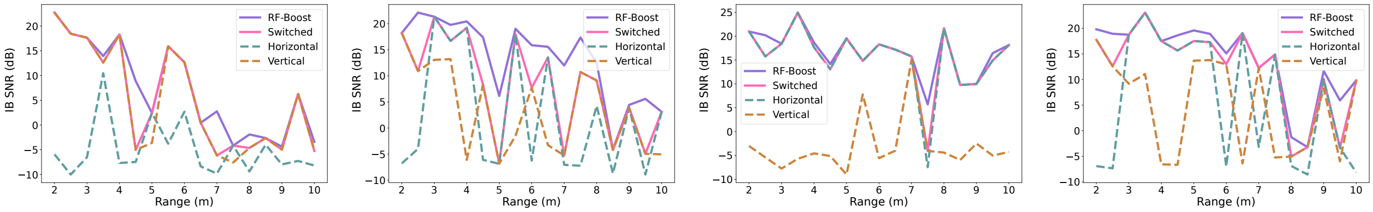
Our algorithm is summarized in Alg. 1. Given the optimal polarization angle from the sweep described in §V-A, we perform a binary search on the IB power to find the ideal power. At each iteration, we transmit at the selected angle (both IB and OOB) and measure the IB SNR. If the IB SNR is above a threshold τ, then the tag successfully powered and we can further decrease our power. If the SNR is below τ, then the transmit power was too low to power the tag, and we increase the power. After completing the binary search, we return the OOB data from the iteration with the lowest IB power that successfully powered the tag (IB SNR $> \tau$). The dynamic power adaptation can then be run for every tag.

Through both minimizing polarization loss and dynamic power adaptation, RF-Boost is able to maximize the OOB SNR to measure strong UWB channel estimates. It then inverts the channel and performs 1D time-of-flight estimation to estimate the distance [3]. These estimated distances can be combined from multiple antennas through trilateration for 2D or 3D localization similar to prior work [3], [7].

VI. Implementation & Evaluation

Hardware. We constructed a wideband RFID reader similar to past work [3], [7], [9] using three Nuand bladeRF software defined radios, whose PLLs are synchronized using the clock-in/clock-out bladeRF ports. We used the bladeRF's python API to apply the amplitude control in Eq. 1. The IB signal is passed through a Hittite-110378-1 power amplifier. The IB and OOB signals are then combined with ZAPD-21-S+ RF-splitters and connected to our antennas. We leverage the bowtie antenna design proposed in [7]. The received signals are split with ZAPD-21-S+ splitters and routed to the bladeRFs for IB and OOB reception. To minimize phase offsets between the horizontal and vertical signals (which would convert the LP into CP), we used the same length SMA cables for both horizontal/vertical chains. We used SmartTrac RFID tags.

Software. We used a raspberry pi to control the bladeRFs and record the received data. We processed the data on an Ubuntu 20.04 computer. We implemented the EPC Gen 2 protocol.



(a) **Tag Angle: 90° (Vertical)** (b) **Tag Angle: 45°** (c) **Tag Angle: 0° (Horizontal)** (d) **Tag Angle: -45°**

Fig. 5: **In-Band SNR vs Range.** IB SNR vs range for RF-Boost(purple), *Vertical*(brown), *Horizontal*(green), *Switched*(pink) with tags at a)90°b)45°c)0°d)-45°

Baselines. We compared the performance of our system to four baselines. *Vertical* transmits and receives only a vertical polarization (both IB and OOB). *Horizontal* transmits and receives only a horizontal polarization. *Switched* transmits and receives a horizontal and a vertical polarization sequentially and chooses the maximum SNR between the two polarizations. To ensure a fair comparison, these baselines use the same measurements as RF-Boost, the only difference being that it only selects SNRs from a subset of transmit angles (e.g., only 0°, only 90°, or only 0° and 90°). Finally, *RF-Boost (No PA)* runs our system without dynamic power adaptation.[1]

Metrics. 1) *Received Power*: We measured the received power using a spectrum analyzer. 2) *IB/OOB SNR*: We measured the signal-to-noise ratio (SNR) of IB and OOB signals. 3) *Localization Error*: We measured the localization error as the difference between the estimated and ground truth distances. We precisely measured the ground truth with a tape measure.

VII. Results

A. Received Power vs Transmit Angle

First, we quantified our ability to successfully construct LP polarizations at different TX angles. We place our two TX antennas at a fixed distance from an LP RX antenna. We connect the RX antenna to a spectrum analyzer and measure the received power with a resolution of 1dB. We then transmit different TX angles with a sweep size of 10° and record the received power. We repeat this with various receive antenna angles. We normalize each experiment to a maximum of 0dB.

Fig 6 plots the received power vs transmit angle for a receive antenna at 0°(purple), 45°(brown), 90°(pink), and -45°(green).

We note that when receiving on a 45° antenna, our system measures a maximum of 0dB at 30° and 40°, and a minimum of -18dB at -50°. This is expected since we receive high power when transmitting a signal near parallel to the receive antenna and a low power when transmitting near perpendicular. Similar patterns exist for other receive angles. This demonstrates that RF-Boost successfully constructs LP signals across all angles.

B. In-Band SNR vs Range

Next, we quantified the read range of RF-Boost. We placed our transmitter and receiver at a fixed location 3.24m apart with lossy foam between the antennas. We then placed a box with 4 tags at 0°, 45°, 90°, and -45° at a distance from and centered between the TX and RX. We define the range to be the one-way distance from the TX to the tag (equivalent to the distance from the RX to the tag). We ran our IB sweep as described in §IV and recorded the IB SNR at each transmit angle. We repeated this experiment 5 times per range and took the max SNR across trials. We then increased the range in intervals of 0.5m and repeated the experiment. We compared to three baselines: *Vertical*, *Horizontal*, and *Switched* (See §VI).

[1] We do not include a CP baseline, since CP signals experience phase offsets in the presence of tag rotations, making fine-grained phase-based localization infeasible [7].

	IB SNR (dB)							
Tag Angle	90°		45°		0°		-45°	
	10^{th}	50^{th}	10^{th}	50^{th}	10^{th}	50^{th}	10^{th}	50^{th}
RF-Boost	-3.7	6.2	3.9	15.8	9.8	18.1	3.1	17.5
Horizontal	-9.5	-7.2	-7.8	-3.8	9.8	17.2	-7.6	10.1
Vertical	-5.5	0.4	-5.6	3.8	-6.7	-4.5	-6.4	9.2
Switched	-5.1	2.4	-5.0	9.1	9.9	17.2	-3.2	14.8

TABLE I: **IB SNR Across Ranges** The table shows the 10^{th} and 50^{th} percentiles of the IB SNR across all ranges for tags at 90°, 45°, 0° and -45°.

Fig. 5 plots the IB SNR as a function of range for RF-Boost and the three baselines for the tag at 90°, 45°, 0°, and -45°. Table I shows the 10^{th} and 50^{th} percentile of the IB SNR across ranges for tags at all four angles(90°, 45°, 0°and -45°) for RF-Boost and the mentioned baselines. We note:

- For tags at 45° and -45°, RF-Boost's 10th percentile SNRs are 3.9dB and 3.1dB, respectively. In contrast, *Switched* is only able to read -5dB and -3.2dB. RF-Boost's ability to read a positive SNR across almost all distances shows the benefit of our techniques for improving the robustness of RFID reading.
- For tags at 45° and -45°, RF-Boost's 50th percentile SNR across distance are 15.8dB and 17.5dB, respectively. In contrast, *Switched* is only able to read a 50th percentile of 9.1dB and 14.8dB, respectively. These improvements show that our software-controlled polarization allows us to increase the SNR of tags that have high polarization loss with switched systems.
- For a horizontal tag, RF-Boost reads a 10th and 50th percentile of 9.8dB and 18.1dB. *Switched* reads 9.9dB and 17.2dB. As expected, they are similar since the horizontal tag does not experience polarization loss with switched LP.
- Interestingly, for the horizontal tag at 7.5m, RF-Boost is able to read 5.7dB, while *Switched* reads a negative SNR of -4.1dB. Similar examples exist across other tags at different locations. This is likely due to angle-dependent multipath [13], which allows our 45° or -45° signal to read the tag when the horizontal signals experienced a multipath null. This shows an additional benefit of our system: improved robustness to nulls.
- In some cases, polarizations are able to read a high SNR from a perpendicular tag (e.g., *Vertical* reads an SNR of 15dB from a horizontal tag at 7m). This is likely due to multipath reflections changing the angle of polarization [13] and decreasing the polarization loss (thus increasing the SNR).

C. Out-of-band SNR vs Tag Angle

In this result, we measured the ability of RF-Boost to read

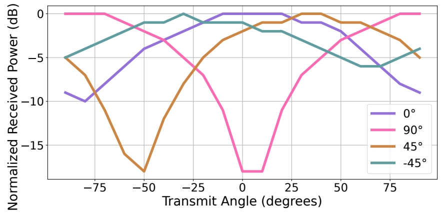


Fig. 6: **Received Power vs Transmit Angle:** Received power vs TX angle for an LP receiver at 0°(purple), 90°(pink), 45°(brown), and -45°(green)

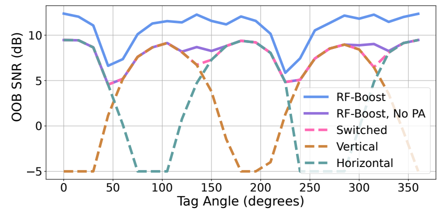


Fig. 7: **OOB SNR.** OOB SNR vs Tag Angle for RF-Boost(blue), *RF-Boost-No PA*(purple), *Switched*(pink),*Vertical*(brown),*Horizontal*(green)

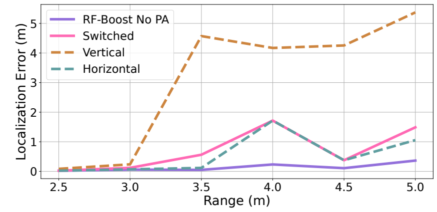


Fig. 8: **Localization Error vs Range.** Localization error vs range for *RF-Boost-No PA*(purple), *Switched*(pink),*Vertical*(brown),*Horizontal*(green)

a high OOB SNR across all tag angles. We placed our transmitter and receiver at a fixed location 1.8m apart. We placed a tag at a fixed distance of 1.7m from and centered between the TX and RX[2]. We ran Alg. 1 and recorded the median OOB SNR across all frequencies. We repeated this experiment 10 times per tag angle and averaged across trials. We then rotated the tag in intervals of 15° and repeated the experiment. We clip the SNRs at a min of -5dB. We compared the performance of our system to *Vertical*, *Horizontal*, *Switched*, and *RF-Boost (No PA)* (See §VI). Fig. 7 plots the OOB SNR vs. tag angle for RF-Boost and the mentioned baselines. We note:

- *RF-Boost (No PA)* outperforms *Switched* at 135° and 315° (8.7dB vs 6.7dB and 9dB vs 6.5dB, respectively). This demonstrates the benefit of our techniques for constructing various LP angles to improve SNR across tag angles.
- Interestingly, *RF-Boost(No PA)* and *Switched* both read 4.6dB at 45°. This is likely due to angle-dependent multipath [13] causing our 45° signal to be weaker than the 90° signal.
- RF-Boost outperforms all baselines by at least 1dB and a median of 2.7dB across all tag angles. This shows the value of our dynamic power adaptation for maximizing OOB SNR.

D. Localization Accuracy vs Range

Finally, we evaluated the localization range of RF-Boost. We placed the transmitter and receiver at a fixed location 1m apart. We placed a -45° tag at a distance from and centered between the TX and RX. We define our range to be the one-way distance from the tag to the transmitter (equivalent to the distance from the tag to the receiver). We ran our sweep described in §V-A and used the resulting data to perform time-of-flight estimation to produce a 1D distance estimate. We repeated this experiment 10 times per distance and took the average error across trials. We then increased the range in intervals of 0.5m and repeated the experiment. To highlight the benefit of our polarization on range, we compare *RF-Boost (No PA)* to our baselines: *Switched*, *Horizontal*, and *Vertical*.

Fig. 8 plots the average localization error vs range for RF-Boost and the mentioned baselines. We note the following:

- *Horizontal* is only able to successfully localize until 3.5m, with 11cm of error at this location. Beyond this, it has 170cm and 38cm of error at 4m and 4.5m, respectively. This is due to its polarization loss, which limits the localization range.
- Interestingly, *Switched* achieves an even shorter range, with a 56cm of error at 3.5m. This is likely caused by the horizontal and vertical signals having similar OOB SNRs but different localization performances. Since both signals have a similar SNR, *Switched* may choose the vertical signal for localization despite worse performance. This shows that sweeping only two angles is not sufficient to increase the localization range, since a large polarization mismatch still occurs at -45°.
- RF-Boost successfully localizes until 4.5m, with only 11cm of error at this location. Even at 5m, the error is only 36cm. This range is almost a 30% improvement over the best baseline, demonstrating the benefit of RF-Boost's software-controlled polarization for improving localization range.

[2] We performed a one-time calibration to ensure the horizontal and vertical receive chains measured equivalent OOB SNRs for horizontal/vertical tags.

VIII. Conclusion

In this work, we demonstrated software-controlled polarization for increasing read and localization range by constructing linear polarizations at any angle to minimize polarization loss. We designed this technique into an efficient discovery protocol that allows us to read and localize tags at unknown angles with negligible polarization loss. Finally, we introduced a dynamic power adaptation scheme to maximize out-of-band SNR.

Acknowledgments We thank the anonymous reviewers and the Signal Kinetics group for their help & feedback. This research is sponsored by NSF (Awards #1844280&#2044711),Sloan Research Fellowship,&MIT Media Lab.

References

[1] D. Kim and J. Yeo, "Dual-band long-range passive rfid tag antenna using an amc ground plane," *IEEE TAP*, 2012.
[2] C.-H. Loo, K. Elmahgoub, F. Yang, A. Elsherbeni, D. Kajfez, A. Kishk, T. Elsherbeni, L. Ukkonen, L. Sydanheimo, M. Kivikoski *et al.*, "Chip impedance matching for uhf rfid tag antenna design," *Progress In Electromagnetics Research*, vol. 81, pp. 359–370, 2008.
[3] Y. Ma, N. Selby, and F. Adib, "Minding the billions: Ultra-wideband localization for deployed rfid tags," in *MobiCom*, 2017, pp. 248–260.
[4] D.-J. Lee, S.-J. Lee, K.-S. Kim, and J.-W. Yu, "Compact polarization diversity antenna using a pair of parallel dipoles for mobile rfid," in *2013 APMC*, 2013, pp. 1061–1063.
[5] Impinj xArray RFID Gateway, https://www.impinj.com/products/readers/impinj-gateways, 2022.
[6] Y. Yan, A. Sharif, J. Ouyang, C. Zhang, and X. Ma, "Uhf rfid handset antenna design with slant polarization for iot and future 5g enabled smart cities applications using cm analysis," *IEEE Access*, 2020.
[7] L. Dodds, I. Perper, A. Eid, and F. Adib, "A handheld fine-grained rfid localization system with complex-controlled polarization," in *ACM MobiCom '23*, 2023.
[8] T. Boroushaki, M. Lam, L. Dodds, A. Eid, and F. Adib, "Augmenting augmented reality with Non-Line-of-Sight perception," in *NSDI*, 2023.
[9] T. Boroushaki, L. Dodds, N. Naeem, and F. Adib, "Fusebot: Rf-visual mechanical search," *Robotics: Science and Systems 2022*, 2022.
[10] P. Nikitin and K. Rao, "Performance limitations of passive uhf rfid systems," in *2006 IEEE APS International Symposium*, 2006.
[11] P. Nikitin, K. Rao, and R. Martinez, "Differential rcs of rfid tag," *Electronics Letters*, vol. 43, pp. 431 – 432, 02 2007.
[12] Q. W. Lin and X. Y. Zhang, "Differential rectifier using resistance compression network for improving efficiency over extended input power range," *IEEE T-MTT*, 2016.
[13] T. Manabe, K. Sato, H. Masuzawa, K. Taira, T. Ihara, Y. Kasashima, and K. Yamaki, "Polarization dependence of multipath propagation and high-speed transmission characteristics of indoor millimeter-wave channel at 60 ghz," *IEEE Transactions on Vehicular Technology*.