

Localization and Tracking of Ambient RF Sources with Analog Backscatter Tags

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Abstract—Analog backscatter communication enables ultra-low-power and low-cost wireless connectivity, making it a promising alternative to traditional RFID systems. Although analog backscatter systems offer simplicity, they are by design less capable compared to their digital backscatter counterparts. A key drawback of existing analog backscatter systems is their single-tag operation, which poses limitations for applications that require multiple tags to function simultaneously. In this paper, we propose a novel low-cost analog backscatter system that allows multiple tags to sense the channel concurrently, thereby enabling signal strength-based localization and tracking of ambient RF sources. The ability to localize RF sources is essential for interference management, security, and optimization of wireless networks, particularly in dynamic environments. We evaluate our system in indoor settings, and demonstrate localization accuracy of RF sources with an average error of 20 cm in a 3 m range, without requiring calibration. Our system is also capable of tracking RF sources with an average speed up to 0.6 m/s with an average power consumption of 526 μ W, making it a promising solution for real-time and energy-constrained applications.

Index Terms—Analog Backscatter, Channel Sensing, Localization, Tracking, Ambient RF Sources

I. INTRODUCTION

Backscatter communication is a promising technology for low-power, and low-cost wireless connectivity, enabling applications in the Internet of Things (IoT), smart cities, and healthcare [1]–[4]. It operates by reflecting and modulating an incident radio frequency (RF) signal to encode information, eliminating the need for power-intensive transmit circuitry [2], [5]. While digital backscatter systems modulate information using discrete signal levels, analog backscatter systems encode data through continuous variations of a signal property such as the amplitude, phase, or frequency [6], [7]. This shift to analog backscatter eliminates the need for both power-hungry components such as analog-to-digital converters (ADCs) and for digital frame structures. This approach further reduces power consumption and system complexity, making it particularly attractive for ultra-low power applications [7]–[9].

Recent work in analog backscatter has demonstrated the feasibility of on-device signal strength measurements using analog backscatter tags, enabling applications such as localization, tracking, and sensing [10]. Some studies have investigated the use of multiple analog backscatter tags by assigning harmonic-based identification codes to each tag [6], [9]. However, existing work on signal strength-based channel estimation in analog backscatter systems has been limited to

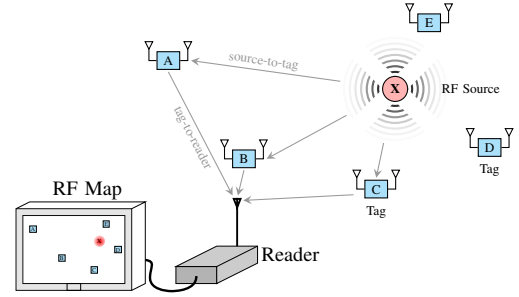


Fig. 1. System overview. Multiple analog backscatter tags (Tag A to E) are deployed in the environment at known locations. A reader constantly monitors the backscatter signals from each tag (tag-to-reader channel). The backscatter signal encompasses information about the incident signal strength (from source-to-tag channel) at each tag. The reader builds a spectrum map (RF Map) of the environment with possible locations of ambient RF sources from the backscatter signal data.

single-tag operation, making it unsuitable for scalable multi-tag scenarios. This limitation arises because the backscatter signals from multiple tags overlap in the frequency domain, causing interference and ambiguity in the received signal. In this work, we address this challenge and propose a scalable solution. Scalability is a critical requirement for applications such as inventory management and object tracking, where multiple tags must be queried simultaneously.

The problem addressed in this work is timely. Localizing RF sources through a real-time and energy-constrained system plays a crucial role in various applications, from wireless network optimization to security and surveillance [11]–[15]. By identifying interference sources such as rogue base stations, and optimizing spectrum allocation, it enhances network performance [16], [17]. In security applications, it helps detect unauthorized transmitters, RF-based intrusions, and covert communication devices [18]–[20]. For IoT and smart infrastructures, it ensures the reliable operation of RF-based IoT devices and facilitates fault detection [21]. In industrial settings, it supports predictive maintenance by monitoring RF emissions and improves autonomous vehicle navigation in GPS-denied environments [22]. Additionally, it aids emergency rescue in locating RF signals from trapped individuals and helps monitor RF exposure levels in healthcare facilities [23], [24].

Figure 1 illustrates the overview of the system of the proposed method. We introduce a system that enables real-time localization and tracking of ambient RF sources using

analog backscatter tags and a backscatter reader. Our approach leverages the on-device received signal strength indicator (RSSI) estimation capabilities of the analog backscatter tags to measure the incident signal power at each tag [10]. Leveraging backscatter technology, the system avoids the complexity and power demands of active radios, making the system low-cost, energy-efficient and well suited for battery-free operation using ambient energy harvesting [2], [8]. This allows for scalable deployment in a wide range of environments.

In our work, we use received signal strength measurements at the tag to locate the signal source. Furthermore, we introduce a method for reliably collecting RSSI measurements from multiple tags at the reader, even in the presence of multipath effects and interference caused by varying channel conditions along the tag-to-receiver path. The backscatter signals from each tag encode the corresponding RSSI at each tag. Hence, the frequency spectrum enables the backscatter reader to decode the per-tag RSSI values as *frequency shifts*. Using these signal strength measurements, the reader constructs a map of the environment, estimating the locations of ambient RF sources in the vicinity of the backscatter tags. This is achieved through multilateration which is an RSSI-based localization algorithm as it can infer the transmitter location by analyzing relative signal strengths from spatially distributed tags without requiring precise time synchronization or ranging hardware.

Achieving this is challenging for several reasons. When multiple tags share the same harmonic frequencies, it leads to signal ambiguity. As analog tags do not have an ID, the identification of tags is challenging. We solve these problems by allocating unique frequency chunks to tags. The RF source or its operating frequency is unknown a priori, thus our method must operate independently of the signal's carrier frequency. We leverage the fact that commodity RF antennas are designed to operate comparatively well across a wider range of frequencies than their resonant frequency. On the other hand, we use a relative positioning approach using the multilateration, which sidesteps the need for absolute RSSI values and allows us to work with relative signal strength measurements.

Our work advances the state-of-the-art by utilizing analog backscatter tags, drastically reducing the overall system power consumption while enabling real-time tracking of ambient RF sources, making RF localization more practical and scalable for a wide range of applications.

We show that:

- multiple analog backscatter tags can measure the channel RSSI simultaneously;
- the system can localize and track ambient RF sources in real-time using analog backscatter tags, without the need of an extensive calibration step;
- the system can be used to track the movement of ambient RF sources up to 0.6 m/s.

To the best of our knowledge, this is the first work that demonstrates the use of analog backscatter tags to localize and track ambient RF sources in real-time.

II. RELATED WORK

The use of analog backscatter tags for localization of RF sources builds upon several key areas of research, including backscatter communication, and RF-based localization.

RF-based Localization: Localization of an RF source is a challenging problem due to the complex nature of RF propagation, which involves multipath fading, shadowing, and interference. ORAN-Sense uses timing differences in 5G-networks to localize RF sources using low-cost spectrum sensors in an outdoor environment [25]. Durgin *et al.* introduce the concept of using backscatter tags for RF source localization in their digital twin framework [13], while Ahmed *et al.* propose a system that leverages commodity radio-frequency identification (RFID) tags to achieve similar objectives [14]. However, these approaches either require significant power due to the use of a commodity RFID reader or lack real-time tracking capabilities. Hussein *et al.* propose a passive frequency comb generation system for ranging applications, which employs a frequency comb generator to produce a series of evenly spaced frequencies that are then mapped to a free space path loss (FSPL) model [26]. However, this method requires the RF source to be equipped with a frequency comb generator, which is impractical when the source is unknown.

RSSI-based Localization: RF-based localization has been widely studied, with techniques ranging from received signal strength indicator (RSSI)-based methods to time-of-flight (ToF) and angle-of-arrival (AoA) estimation. McPartlin *et al.* evaluate the performance of RSSI-based localization techniques using off-the-shelf transceivers in an indoor environment [27]. Hiroyuki *et al.* propose to utilize interference signals for localization, improved with signal dithering to enhance the accuracy of RSSI measurements [28]. Bahl *et al.* introduced the RADAR system, which uses RF-based localization for indoor environments based on RSSI and signal-to-noise ratio (SNR) measurements at the user location [18]. Manikanta *et al.* developed SpotFi, a system that uses AoA for 40 cm level localization accuracy using Wi-Fi signals [29]. While these methods have shown promise, they typically require specific hardware (SpotFi requires the target to have a Wi-Fi chip [29]) or infrastructure, limiting their scalability and applicability. In contrast, our approach uses analog backscatter tags to passively localize and track ambient RF sources, eliminating the need for dedicated transmitters or complex hardware.

RSSI-based localization techniques suffer from different path loss models and multipath fading in different environments, leading to significant variations in the RSSI values received by the tags [30]. Therefore, several methods have been proposed to improve the accuracy of RSSI-based localization, including fingerprinting-based localization using machine learning techniques [31], [32], and probabilistic localization using Bayesian methods [33]. However, these methods typically require prior knowledge of the environment and training processes, which we aim to avoid in our work.

Backscatter Communication: Backscatter communication has emerged as a low-power alternative for wireless communication, enabling devices to transmit data by reflecting

ambient RF signals without requiring an active transmitter. The leading work by Vincent *et al.* demonstrated the feasibility of backscatter communication using ambient radio signals such as TV and cellular signals [5]. Subsequent research extended this concept to support higher data rates and longer ranges [34], [35]. Recent work builds on this foundation to explore the use of analog backscatter sensing, enabling more efficient use of ambient RF sources and backscatter communication [7]–[9]. Our work leverages these advancements but focuses on the unique challenge of using analog backscatter tags for localization and tracking, rather than solely for data transmission.

Backscatter-based Localization: There are two main approaches to localization using backscatter communication: (1) using backscatter tags to localize a source, and (2) using backscatter tags to localize themselves. Relating to the first approach, Ahmed *et al.* proposed a system that uses RFID tags (a type of backscatter tags) to build a map of ambient RF sources based on the RSSI of the signals received by the tags [14]. This system relies on the RSSI measurements from the tags to estimate the location of the RF sources using a USRP N210-based wideband receiver and a dedicated RFID reader, but it does not provide real-time tracking capabilities. Apart from this work, we are not aware of any other systems that use backscatter tags to localize RF sources.

The second approach, which focuses on localizing backscatter tags themselves, has been explored in several recent works. Manikanta *et al.* proposed a system that uses backscatter tags for localization in indoor environments using commodity Wi-Fi devices [36]. Deepak *et al.* demonstrated a system that uses backscatter communication for localization in in-body networks [37]. Luo *et al.* developed a system that uses backscatter communication for localization in fine-grained robotics applications [38]. While these works show the potential of backscatter communication for localization, they typically rely on active RF sources or specialized infrastructure. In contrast, our work focuses on localizing and tracking ambient RF signal sources themselves, using passive analog backscatter tags without the need for additional receivers.

Our work combines analog backscatter communication with ambient RF source localization and tracking. In contrast to previous work that relies on extensive calibration [14], our system is designed to work with minimal calibration, making it more practical for deployment and use in real-world scenarios, unlocking new opportunities for IoT and smart environments.

III. SYSTEM OVERVIEW

In this work, we propose a proof-of-concept localization and RF mapping technique using analog backscatter tags (hereafter referred to as *tags*), which sense the wireless channel with minimal energy consumption. A prototype of the tag is shown in Figure 2a, and its block diagram is illustrated in Figure 2b.

Tag Hardware: The tag prototype as shown in Figure 2a, consists of two antenna ports (one for sensing the incident signal strength, and the second for backscatter module) on either side of the prototype. Two potentiometers (black knobs

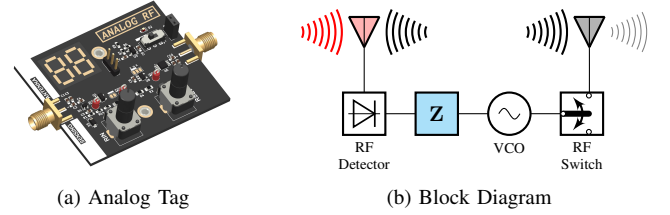


Fig. 2. Analog Backscatter Localization Tag. (a) The physical view of the analog tag design. The Tag has been designed to enable multi-tag capabilities that are essential in this work. (b) The block diagram illustrating an abstract view of the analog tag design.

in Figure 2a) set distinct voltage levels to limit each tag prototype operating in a unique frequency bandwidth, based on Eq. (1) and (2). The prototype is made battery powered to ensure ease of deployment during the experiments.

Challenges in Channel Estimation: It is challenging to estimate the RF source-to-tag channel at the receiver, as the tag-to-receiver channel can significantly alter the characteristics of the backscattered signal. In a typical backscatter system, the received signal at the reader is a product of two separate wireless channels, from the RF source to the tag, and the tag to the reader. Due to this multiplicative nature, variations due to multipath or distance in the tag-to-reader channel alter the information about the RF source-to-tag channel embedded in the backscattered signal. As a result, the amplitude of the received signal does not provide a direct or reliable mapping to the RF source-to-tag channel characteristics alone, making accurate channel estimation a non-trivial task.

Alternative representations, such as phase and frequency, must therefore be considered. However, encoding RSSI in phase would require dynamically adjusting the impedance of the tag's reflection, and even then the measurement remains entangled with the unknown channel phase. In contrast, frequency shifts offer a robust alternative as they allow encoding without interference from distance or channel phase effects, provided that the frequency deviations are larger than typical Doppler shifts and carrier frequency offsets. Building on previous work in analog backscatter [10], we extend the approach to enable concurrent operation of multiple tags. By eliminating the need for active receivers, our method utilizes passive, low-power backscatter tags, making it particularly well suited for scalable and long-term deployment.

Concurrent Tags: Having multiple tags to localize increases accuracy, as later illustrated in Figure 6, as each tag response gives away a possible location of the RF source, a possibility to filter out outliers, the relying on just 3 tags for triangulation-based methods. However, when multiple analog tags are deployed, their frequency responses overlap in the spectrum, making it difficult to associate the tag data. To solve this, we assign each tag a pre-set, narrow switching frequency band (a few kHz wide), unlike prior work where all tags shared the same frequency band [10]. Figure 3 illustrates the difference between the prior-art design and our proposed design, which enables frequency division to allow multiple (four) tags to operate concurrently. This separation avoids frequency overlap

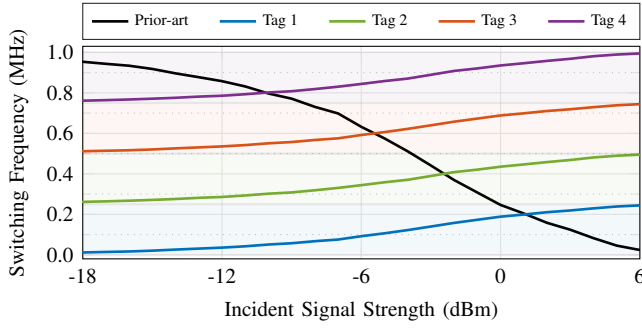


Fig. 3. Comparison of prior-art design and the proposed design, which enables frequency division to allow multiple tags to operate concurrently.

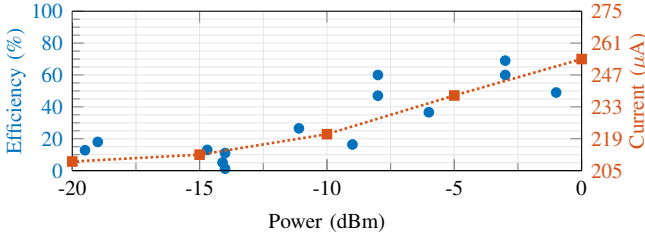


Fig. 4. Relationship between energy harvesting efficiency [39] and the current consumption of the VCO at different switching frequencies. Higher input power yields higher efficiency, enabling the tag to consume higher current to generate higher frequencies.

and interference, enabling the reader to distinguish multiple tags based on their unique frequency assignments. The tags operate continuously, always backscattering data about the incident signal strength, while the reader remains always on, continuously receiving these backscatter signals. This continuous operation eliminates the need for any synchronization between the concurrent tags and the reader.

Energy Harvesting and Frequency Adaptation: The tags sense the strength of incoming signals independently of the signal's carrier frequency (frequency agnostic-behavior), specifically the tag's antenna acts as a passband filter, harvesting energy from the incident electric field within its operational frequency band to generate a voltage for switching. In contrast to the inverse mapping approach used by Padmal *et al.* [10], we employ a voltage-controlled oscillator (VCO) that produces a switching frequency with a monotonically increasing, one-to-one mapping to the incident signal strength. By assigning distinct frequency ranges to multiple tags and aligning their switching behavior with the available received power, our approach supports concurrent operation while naturally adapting each tag's power consumption to environmental RF conditions. Specifically, because higher switching frequencies consume more energy, a tag only reaches its maximum frequency when there is sufficient incident power to sustain this increased consumption. In other words, the tag operates at lower frequencies under weaker incident power that consumes less energy, and increases its switching frequency only when more power is available, thereby intuitively scaling its power usage according to the ambient RF energy.

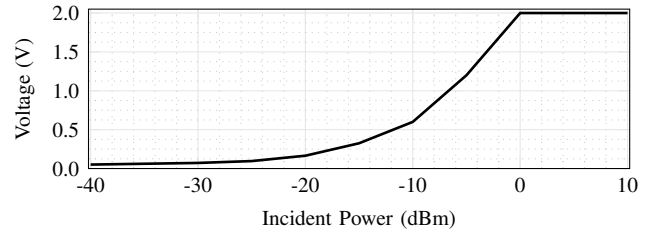


Fig. 5. The relationship between the incident power and the generated voltage at the tag. Higher incident power leads to higher voltage, which in turn supports higher switching frequency and harvesting efficiency. The clipping at 2 V occurs due to a design constraint.

We verify this concept in Figure 4, that shows the relationship between RF energy harvesting efficiency (blue markers) and current consumption (orange markers) of the tag as a function of incident RF power and switching frequency. The energy harvesting efficiency values are obtained from the work by Valenta *et al.* [39]. We use a Keysight E36313A power supply to supply the power to the tag and record the current consumption values at different incident RF power levels. We also measure the current consumption of the bare VCO integrated circuit (IC) (LTC6900) at different switching frequencies using LTspice simulations. The results are comparative to the real measurements with an average negative offset of 32 μA . The results are not shown in the plot for clarity. This difference stems from the additional components in the tag design, such as the ADG902 RF switch [40] and the ADA4505 buffer IC [41], which are not present in the LTspice simulation. The relationship between the RF energy harvesting to current consumption coincides: higher input power leads to higher efficiency, enabling the tag to operate at higher switching frequencies.

System-Level Operation and Localization: We design a battery-free tag that harvests energy from the incident RF signal. This incident signal is then used to power the VCO and other components. Figure 5 shows the relationship between the incident power and the generated voltage at the tag measured at the output of the RF Detector block shown in Figure 2b. The generated voltage is significantly higher when the incident power is above -10 dBm . The maximum voltage is limited to 2 V due to a design constraint to avoid the saturation of the VCO to slip into a frequency range that is not allocated to the tag, which we discuss in the next section. If the incident power is below -10 dBm , the generated voltage may not be sufficient to power the VCO instantaneously, limiting the tag's ability to continuously monitor the channel.

At a high level, the system consists of a fixed reader and multiple tags placed at known locations. Each tag generates a backscatter signal with a unique switching frequency that varies according to the incident signal strength. The reader processes these signals by filtering out each frequency peak from the spectrum to isolate the signals from individual tags, identifying each tag based on its assigned frequency bandwidth using the bandwidth map shown in Figure 9, and mapping the observed switching frequency to its corresponding RSSI

value, as illustrated in the same figure. With the RSSI values from each tag, the receiver then estimates the distance from the RF source to each tag using a simple path loss model. Finally, these distance estimates are used for multilateration to approximate the RF source location, rendering a 2-D map.

Receiver Options: We use a USRP B210 SDR as the backscatter receiver. However in the 6-tag deployment, we only utilize a bandwidth less than 2 MHz. Therefore, the USRP can be directly swapped with a low-cost RTL SDR dongle (with over 3.2 MHz bandwidth) that costs less than \$50, to significantly reduce the experimental setup cost [42].

A. Multiple Tag Operation

There are two known approaches in the literature to enable multiple tag operation for analog backscatter systems. The first method uses a VCO to generate pulse-width modulation (PWM) signals with varying duty cycles, producing distinct harmonic patterns for each tag [6]. However, this approach requires a complex receiver design, as the receiver must differentiate a tag from the frequency spectrum by analyzing the harmonic content while the fundamental frequency is also changing due to different incident signal strengths. This makes it challenging to multiplex the VCO for signal strength measurements. The second method employs frequency-selective querying, where tags respond to specific reader frequencies [43], offering simpler implementation but introducing delays due to sequential querying that limits real-time localization and tracking.

We propose a new multi-tag analog backscatter design using a VCO-based PWM generator that assigns each tag a fixed, distinct frequency range. Unlike the prior design [10], which uses an inversely proportional frequency-to-signal strength relationship (via the LTC6906 [44]), our design employs the LTC6900 [45], offering a direct proportionality that aligns better with intuitive power dynamics which creates higher switching frequencies for higher signal strength. This change reduces spectral overlap and supports up to 20 times more tags, albeit with increased power consumption. Additionally, we introduce a resistor-based tuning mechanism to assign unique frequency ranges per tag, enabling scalable and interference-free multi-tag operation. The LTC6900 requires two resistors, R_{SET} and R_{IN} , to set the output frequency range of the VCO [45]. We derive the required resistor values using Eq. (1) and Eq. (2) where $F = \frac{f_{max}}{f_{min}}$. The values f_{min} and f_{max} are in MHz corresponding to the minimum and maximum switching frequency range of a tag.

$$R_{SET} = \frac{F \times 10^3}{(8F + 2)f_{max}} \quad (1)$$

$$R_{IN} = \frac{F \times 10^4}{55(F - 1)f_{max}} \quad (2)$$

The impedance block ($\mathbf{Z}$) in the block diagram of the tag as shown in Figure 2b consists of R_{SET} and R_{IN} to enable the multi-tag capability ensuring that the switching frequency range of each tag does not overlap with another

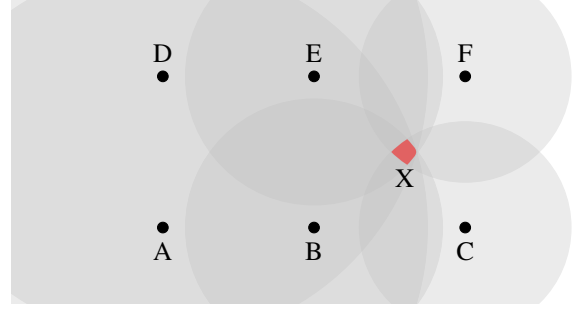


Fig. 6. Illustration of the multilateration process. The black dots represent the tags, and the circles around them represent the estimated distance to the RF source derived from the path loss model. Circles with very large radii are discarded to filter out outliers as they are at limits, while circles with radii below the maximum limit, contribute to the multilateration. The intersection of the circles represents the estimated location of the RF source (X).

tag. Figure 3 shows the difference between the switching frequency ranges of the multi-tag designs compared to the single tag design in prior work [10]. The old design allows the switching frequency to vary across the whole range of the PWM generator IC (LTC6906). The new design divides the switching frequency range into segments for each tag. This ensures that the switching frequency range for each tag does not overlap with another tag at the expense of reduced dynamic switching frequency range for each tag.

Given the 3.2 MHz bandwidth limit imposed to ensure compatibility with low-cost SDR platforms, there is an upper bound on the number of tags the system can support. Our real-world experiments showed that each tag requires approximately 200 kHz of bandwidth to provide reliable readings. Based on this requirement, the system can support up to 16 tags, which is the practical limit for an RTL-SDR receiver. However, using a receiver with a higher bandwidth would allow the system to scale beyond this number.

The switching frequency also affects the power consumption of the tag, with higher switching frequencies leading to increased power usage. Although analog backscatter tags are battery-free and harvest energy from the incident RF signal, this energy is not unlimited, particularly in low-power environments or when the RF source is far from the tag. In such scenarios, tags operating at higher switching frequencies may experience shorter active durations or require longer duty cycles to recharge, potentially reducing sensing granularity. To address this imbalance, a dynamic, power-aware frequency allocation strategy could be used to assign lower switching frequencies to tags with constrained energy availability, or rotating frequency assignments over time to balance energy usage and ensure uniform performance across multiple tags.

B. Localization Model

We derive an expression for the estimated distance (d_i) between the i^{th} tag and the RF source using the received signal power (P_R^i) at the i^{th} tag based on [46] as,

$$d_i = 10^{\frac{C_d - P_R^i}{10n}} \quad (3)$$

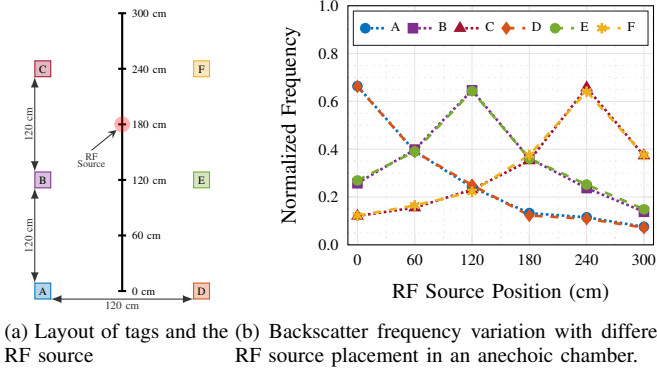


Fig. 7. Experimental setup and backscatter frequency variation in the anechoic chamber. The frequencies are mapped to the tag distance from the RF source (red blob in (a)) using the corresponding incident signal strength at the tags.

where n is the path loss exponent, and C_d is the received signal power at a reference distance d from the tag. We estimate the RF source location using multilateration by combining the distance estimates from multiple tags. Figure 6 illustrates this process. In the figure, each black dot represents a tag. Based on the incident signal strength, each tag outputs a frequency value that can be mapped to a distance (radius) using the path loss model in Eq. (3). We then draw a circle around each tag's position, with the radius corresponding to its estimated distance to the RF source. Typically, circles with larger radii help filter out outliers, while circles with smaller radii contribute to accurately pinpointing the source location. Hence the increased number of tags, help improve the localization accuracy. The overlapping regions of these circles are analyzed, and after filtering out outlier intersections, the remaining intersecting area is identified as the estimated location of the RF source, as shown in Figure 6.

Traditional RF localization systems, such as fingerprint-based methods, rely on an extensive training phase where the RF source is placed at known grid locations, and RSSI values are recorded at each tag to construct fingerprint maps [32], [47]. These maps are then used to train a model for predicting the source location during real-time operation [48]. However, such methods demand significant calibration effort and large training datasets, and are sensitive to environmental changes, as highlighted in RFIMap [14]. In contrast, our approach eliminates the need for a training phase or fingerprint maps, yet achieves a localization accuracy of 20 cm in typical indoor environments, as demonstrated in the next section.

IV. EXPERIMENTS AND RESULTS

In this section, we present the experiments conducted to evaluate the proposed localization and mapping technique using analog backscatter tags. We evaluate the performance of the proposed technique in terms of localization accuracy in an anechoic chamber and an office room.

A. Experiment - Anechoic Chamber

Figure 7 shows the experimental setup. This experiment was done in an anechoic chamber to have a controlled environment

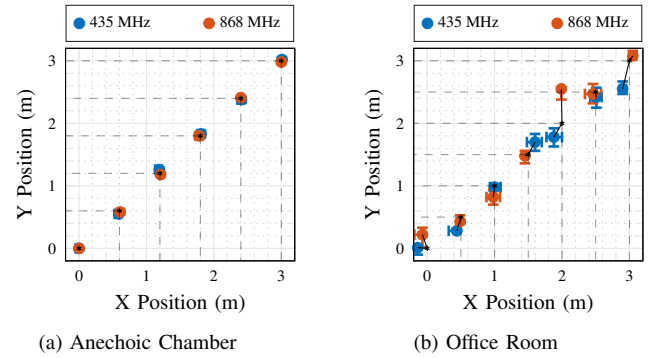


Fig. 8. Estimation of the RF source location in a 2-D Cartesian plane using the tags. The (X,Y) positions correspond to an exploded position ($0, y \in [0, 3]$) along the vertical centerline. Each estimated location is marked with a colored dot, and the true position of the RF source is the intersection of the dashed lines. Thin black lines connect estimates to the true position.

that minimizes reflections and external noise, allowing us to evaluate the performance of the proposed technique in isolation, without interference from other sources and reflections. We place six backscatter tags (A to F) at fixed positions (see Figure 7a) within the anechoic chamber, each assigned with a unique, non-overlapping frequency band of 250 kHz. The placement of the tags is symmetric along the centerline (marked with a black line in Figure 7a). The RF source (USR B210), annotated with a red blob in Figure 7a, moves along this centerline in 60 cm steps, and transmits a continuous wave (CW) signal at 868 MHz with a transmit power of 8 dBm. For each 60 cm position of the RF source, we record the frequency shifts of the tags (that represent the signal strength of the RF source at the tags) using a Rohde & Schwarz ZNL6 spectrum analyzer, capturing a single spectrum trace. The normalized frequency variation of each backscatter tag is plotted against the corresponding position of the RF source on the centerline in Figure 7b. The frequency variation is symmetric with respect to the RF source location (at positions 120 cm and 240 cm) and nearly identical for the symmetric tag pairs (A-D, B-E and C-F) as the RF source is equidistance.

Figure 8a shows the estimated RF source locations relative to ground-truth, in a 2-D Cartesian plane. Since each estimate can deviate both horizontally and vertically from the true source, a Cartesian chart provides a natural way to represent these offsets. In the plot, the x-axis indicates the horizontal displacement from the ground-truth centerline, representing how far the estimate is away from the centerline of the layout. The y-axis indicates the vertical displacement along the centerline, representing how far along the centerline the estimate lies. The true source position is marked with a star, at the intersection of the dashed lines, and each estimate is shown as a red marker for 868 MHz and a blue marker for 435 MHz. The results show that the estimated location of the RF source is close to the true position, with a mean error of 2.8 cm and a maximum error of 8.6 cm. We also experiment with a source frequency of 435 MHz in the anechoic chamber. The results are shown in the same Figure 8a with similar results to those with 868 MHz, as shown in blue dots with a mean error of

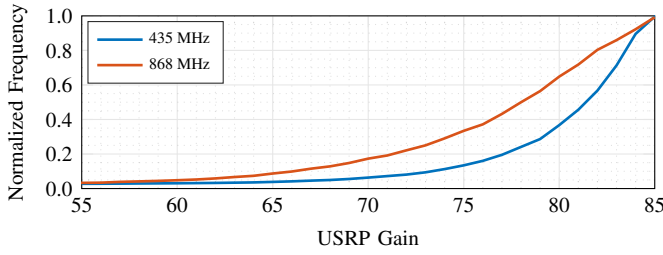


Fig. 9. Frequency to gain mapping for different frequencies. Antenna performance is crucial in the frequency mapping, however the use of relative positioning sidesteps the differences despite the difference in source frequency.

4.5 cm and a maximum error of 12.2 cm.

B. Frequency to Gain Mapping

Our localization model relies on frequency variations in the backscatter signals received from individual analog backscatter tags to accurately estimate the position of an RF source. These variations reflect the signal strength at each tag, which is influenced by the location of the RF source. Crucially, the accuracy of this model depends on a reliable, one-to-one mapping between received signal strength and the switching frequency of the tag. Since antenna performance plays a vital role in this mapping, we use omnidirectional antennas matched to 868 MHz on our tags, rather than wide-band options like log-periodic antennas. Although wide-band antennas support a broad frequency range, they are typically directional [49], making them unsuitable when neither the direction nor position of the RF source is known. Prior work [43] has shown that omnidirectional antennas used in analog backscatter tags maintain near-passband performance over a relatively wide frequency range, with optimal sensitivity around the matched frequency. Hence we evaluate the applicability of our model across different RF source frequencies, with measurements using two commonly used industrial, scientific, and medical (ISM) bands: 435 MHz and 868 MHz.

We record the switching frequency of the backscatter signal using a USRP B210 SDR, at various USRP gain settings, which determine the transmitted signal strength. Figure 9 shows that the backscatter frequency increases with gain for both bands. The red curve (868 MHz) provides a finer mapping than the blue curve (435 MHz), and lies above it, indicating that for the same gain setting, higher signal power is received at 868 MHz due to better antenna matching. Despite minor frequency-dependent gain variations in the USRP hardware [50], the key insight is that both bands exhibit a consistent one-to-one mapping between the backscatter frequency and the signal strength. This is essential, as our localization model only depends on relative frequency variations, not the absolute frequency values.

To ensure that our localization model is agnostic to the RF source frequency, we normalize the frequency shifts from each tag based on the minimum and maximum frequency values of the tag's allocated frequency band. This normalization provides a relative estimate of the RF source location with

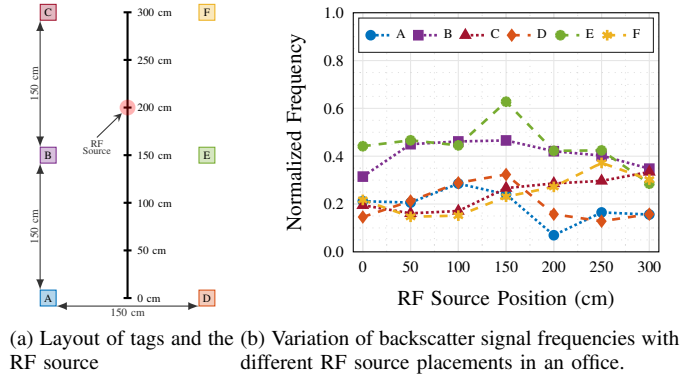


Fig. 10. Experimental setup and backscatter frequency variation in an office room. The frequency variation is mapped to the distance of the tags from the RF source (red blob in (a)) using the corresponding incident signal strength at the tags.

respect to the tags, making the model independent of the absolute frequency values. As long as a consistent one-to-one mapping exists between frequency and signal strength, the model generalizes well across different RF source frequencies. Moreover, if the RF source frequency is known beforehand, the localization accuracy can be further improved by applying the corresponding frequency-to-gain mapping from Figure 9 to better estimate signal strength at each tag. This is validated in Figure 8a, which demonstrates consistent performance for both 435 MHz and 868 MHz frequency bands.

C. Experiment - Office Room

In this experiment, we evaluate the performance of the proposed localization model in a real-world environment, specifically an office room with multiple walls and furniture with people moving around. The office room is a challenging environment for localization due to the presence of unpredictable reflections and multipath propagation.

Figure 10 shows the office room setup. We adopt a similar symmetric setup as in the anechoic chamber experiment, with six backscatter tags (A to F) placed at fixed positions within the office room, each assigned with a unique, non-overlapping frequency band of 250 kHz. The placement of the tags is symmetric with respect to the centerline (black line in Figure 10a). The RF source (USRP) annotated with a red blob in Figure 10a moves along the centerline in 50 cm steps and transmits a continuous wave (CW) signal at 868 MHz with a transmit power of 8 dBm. We perform the experiment in two rounds, with the RF source transmitting at 868 MHz in the first round and at 435 MHz in the second round.

Similar to the anechoic chamber experiment, we record the frequency shifts at each tag using a ZNL6 spectrum analyzer, capturing a single spectrum trace at each 50 cm step position of the RF source. The normalized frequency variation of each backscatter tag is plotted against the corresponding position of the RF source on the centerline in Figure 10b. Compared to the anechoic chamber experiment, the frequency variation of the backscatter signal in the office room is not symmetric with respect to the RF source positions, even though the tags are

symmetrically placed with respect to the centerline. However, the symmetric tag pairs (A-D, B-E and C-F) show similar frequency variations in most of the locations.

Based on the normalized frequency measurements in Figure 10b, we extract the corresponding signal strength at each tag in terms of USRP gain, using the frequency-to-gain mapping shown in Figure 9. For instance, a normalized frequency of 0.0 corresponds to USRP gain of 55, while a normalized frequency of 1.0 corresponds to USRP gain of 85. This extracted signal strength data is then used to estimate the distance of the RF source from the tags using the received signal power model in Eq. (3), assuming a path loss exponent of $n = 2$, which corresponds to free-space propagation conditions following the inverse-square law typically observed in environments with unobstructed line-of-sight [51]. Figure 8b shows the estimated location of the RF source in a 2-D plane using the backscatter tags. The true position of the RF source is the dashed line intersection, and each estimated location is marked with a red dot for the 868 MHz band and a blue dot for the 435 MHz band. The results show that the estimated location of the RF source is approximately close to the true position, with a mean error of 18 cm and a maximum error of 55 cm for the 868 MHz band, and a mean error of 20 cm and a maximum error of 46.1 cm for the 435 MHz band.

D. Multi-Path Conditions

Figure 8b shows that in the office environment, the frequency variation between the tags is not perfectly symmetric with respect to the RF source, even though the tags are placed symmetrically. This contrasts to the measurements in the anechoic chamber (see Figure 7b), where the frequency shifts are symmetric, as expected in an ideal reflection-free environment. The asymmetry in the office environment is due to realistic propagation effects such as multipath and reflections from nearby walls and furniture. For example, tags D, E, and F are located closer to a wall, while tags A, B, and C are positioned farther away. As a result, the tags near the wall receive stronger reflected signals, leading to slight distortions in the frequency response, particularly noticeable at RF source positions 0 cm and 150 cm in Figure 10b. Despite using simple analog backscatter tags that lack complex signal processing capabilities, our system handles such multipath effects robustly. We do this by leveraging the spatial diversity of the tags instead of using all measurements equally. We select subsets of tags at a time to localize the RF source. This allows us to identify and exclude data from tags whose readings are likely affected by multipath, effectively filtering out anomalies and outliers. This strategy maintains system simplicity while significantly improving localization accuracy, suggesting that our method is well-suited for deployment in realistic, multipath-prone environments.

E. Mobile RF Sources

RF source localization is a challenging task, especially when the RF source is moving at high speeds. Prior work requires more than 60 seconds to perform a frequency sweep [14].

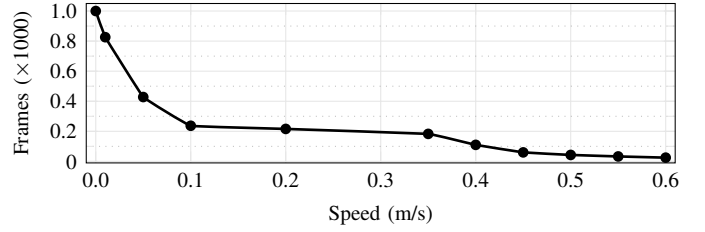


Fig. 11. Tracking of the RF source with speed. The spectrogram frames track the variations in the backscatter frequency. As the RF source moves faster, frequency variations are present in fewer frames, limiting the accuracy.

This inherent delay limitation is not suitable for real-time localization of a moving RF source as when the location estimation is performed, the RF source may have moved to a different location. There are two main reasons why our system can localize moving RF sources: First, our method does not require a calibration process that delays the processing time of moving RF sources. Second, the instantaneous frequency mapping property of analog backscatter tags provides fast frequency data, making the localization task faster. We evaluate the performance of our work with a moving RF source.

In this experiment, we place the RF source (USRP B210) on a moving table and a backscatter tag on a stationary table at a distance of 60 cm from the RF source. We record a video to capture the movement of the RF source to estimate the speed of the motion by analyzing the location of the RF source and the frame rate of the video, and a ZNL6 spectrum analyzer to record the spectrogram of the backscatter signal. The RF source is moved at different speeds, along a perpendicular line to the tag, and the spectrogram is traced at each speed.

As the RF source moves towards the backscatter tag, the backscatter signal frequency increases, and as the RF source moves away from the backscatter tag, the backscatter signal frequency decreases. We measure the number of frames in the spectrogram that shows an increase or decrease in the signal frequency from the steady state frequency of the backscatter signal that is recorded when the RF source is stationary. Figure 11 shows the number of frames in the spectrogram that track the frequency variations of the backscatter signal as the RF source moves at different speeds. When the RF source movement is slow, the frequency variations are present in more frames. As the RF source moves faster, the frequency variations are present in fewer frames, limiting the accuracy as the frequency variations are not captured in the spectrogram.

A receiver such as the USRP B210 can capture up to 56 MHz of bandwidth in real time. The backscatter tags operate in a finite frequency band of few megahertz wide, with each tag operate in a unique kilohertz-wide frequency band. The USRP spectrum captures all the backscatter tags in the same frequency band in real time as it requires only a few megahertz of bandwidth from the 56 MHz upper limit. Hence the results show that we can localize and track the RF source even when it is moving at speeds of up to 0.6 m/s. Utilizing a much capable receiver with higher sampling rate, will make it possible to track RF sources moving at even higher speeds.

V. DISCUSSION

Our proposed system demonstrates the proof-of-concept of the feasibility to localize and track ambient RF sources by enabling multiple analog backscatter tags to operate concurrently to allow simultaneous channel sensing.

Frequency Band Selection: Tag-specific frequency bands are defined using discrete resistors in the VCO. We preset these resistors during fabrication using fixed resistors or potentiometers, or adjust them dynamically using programmable digital potentiometers or digitally controlled switches. While fixed assignment is simple, it leads to unfairness in power consumption across tags. Tags that are assigned higher frequency bands typically consume more power, that result in reduced active duty cycles or sensing rates, especially in low-RF environments. Flexible frequency allocation through dynamic resistor control allows the system to implement frequency hopping and load balancing strategies, thereby enhancing resilience against interference, improving fairness in energy usage, and supporting scalability in multi-user environments.

Energy Harvesting and Operational Range: The effectiveness of backscatter tags heavily depends on their ability to harvest sufficient energy from the incident signals. Tags positioned farther from the RF source receive lower power, which can limit their operating range or make it difficult to generate the desired switching frequency. Incorporating efficient rectifiers and energy storage elements could help maintain consistent performance over a wider area.

Oscillator Power Consumption and Trade-offs: We explored different voltage-controlled oscillator (VCO) options, such as the LTC6906 and LTC6900, to understand the trade-off between power consumption and stability. While the LTC6900 consumes more power, it offers a wider frequency range and more stable output, enabling support for a higher number of tags with minimal frequency overlap. In contrast, ultra-low-power oscillators may reduce energy demands but suffer from drift and limited tunability, which can impair scalability and frequency separation in dense deployments. Future work will focus on enhancing the system's capabilities and replacing the VCO that we use in this work with a more efficient solution. Tunnel diode-based frequency generators and ring oscillators are promising low-power alternatives for the current VCO to generate kHz-range PWM frequencies [52]. They can significantly reduce the power consumption of an individual tag by several orders of magnitudes, while retaining the proof-of-concept design presented in this work as it is, replacing only the VCO component.

System-Level Observations: Our results indicate that the proposed system significantly improves state-of-the-art approaches by introducing a calibration-free RF source localization mechanism. Moreover, the architecture is inherently scalable, with the potential to support dense tag networks in applications such as asset tracking, smart environments, and ambient RF sensing. Our results is limited to single RF source localization, similar to state-of-the-art. However due to the relative RSSI based multilateration, it shows the potential in tracking another RF source in the vicinity.

VI. CONCLUSIONS

This paper presented a novel approach to RF source localization and tracking using a multi-tag analog backscatter system. We demonstrated that multiple tags can simultaneously measure the RSSI of the same RF source, enabling low-cost localization and tracking without the need for complex calibration procedures, thus providing a significant advantage over existing systems. We experimentally evaluated our system in indoor environments, achieving a mean localization error of 20 cm and a maximum error of 55 cm for static RF sources over a range of 3 m. We further successfully tracked moving RF sources at an average speed of 0.6 m/s. The system operated with an average power consumption per tag of 526 μ W. Finally, we outlined research directions for future work to further enhance the system's design. Our system can effectively localize and track RF sources, providing a promising solution for dynamic environments, while being it suitable for real-time and energy-constrained applications.

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