60GHz Mobile Imaging

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***Abstract*—The future of mobile computing involves autonomous drones, robots and vehicles. To accurately sense their surroundings in a variety of scenarios, these mobile computers require a robust environmental mapping system. One attractive approach is to use 60GHz networking radios in these devices, and capture signals reflected by the target object. The devices can also move while collecting reflection signals, creating a large synthetic aperture radar (SAR) for accurate RF imaging. Our experimental measurements, however, show that SAR provides poor precision in practice, as it is highly sensitive to device positioning errors that translate into phase errors. We address this challenge by proposing a new 60GHz imaging algorithm, *RSS Series Analysis*, which images an object using only received signal strength (RSS) measurements along the device's trajectory. Our algorithm can derive object surface properties at high precision, including location, surface orientation, curvature, boundaries, and material. We tested our system on different common household objects. Results show that it achieves cm-level accuracy in different dimensions, and is highly robust against noises in device positioning and tracking. We believe that this is the first practical mobile imaging system using 60GHz networking radios, and provides a basic primitive towards a detailed environmental mapping systems.**

I. INTRODUCTION

Mobile computing is evolving. For decades, mobile computing centered around users and their movements, whether it was on foot, or on vehicles. However, the next generation of mobile computing and its challenges will likely be defined in the context of a variety of autonomous mobile agents, including drones, self-driving cars, or semi-autonomous robots. A key challenge for the widespread deployment of these autonomous devices is the environmental sensing system, *e.g.*, a mobile imaging system that captures the position, shape and surface material of nearby objects. The system must provide accurate and robust information about the device's surrounding at night or in dark areas while it's moving. High accuracy is critical (cm-level [1]), and the system should be compact, lightweight and cost-effective for a variety of devices.

None of the existing solutions meet these needs. Traditional visible light imaging systems (*e.g.*, cameras) perform poorly in dark or low-light conditions, and lack the precision desired by these applications. Acoustic solutions have been used successfully for ranging over short distances [2], [3], but are easily disrupted by background noise and fail over longer distances. Prior works on RF imaging use WiFi bands to track human motion and activity [4], [5], detect metal objects [5], and map large obstacles [6]. But they require costly specialized hardware or large antennas unsuitable for mobile devices. A recent project reuses WiFi communication devices with multiple antennas to image objects, but its precision is fundamentally limited by WiFi's large wavelength [7]. Finally, while today's mm-wave imaging systems can offer accurate object imaging [8], [9], they require specialized hardware like large lens and FMCW circuits, and do not fit the size or cost constraints of commodity mobile devices.

RF Imaging via 60GHz Networking Radios. One attractive approach is RF imaging using commodity 60GHz networking radios to capture 60GHz signals reflected from objects. Such a high-frequency RF radar system has several key advantages over alternatives. *(1)* 60GHz links are highly directional, making them relatively immune to interference from environmental factors like ambient sound or wireless interference. *(2)* 60GHz beams exhibit good reflective properties, and work reliably both indoor and outdoor. *(3)* 60GHz radios are inexpensive ($<$\$40 [10]) and small enough to fit in today's smartphones.

The challenge of mobile RF imaging is achieving high accuracy within a small device. From radar theory [11], it holds for the antenna size and the optimal accuracy (resolution) that $resolution = wavelength \times distance/antenna\ size$. For smartphone-sized antennas, even high-frequency radios (5–120GHz) can produce resolutions no better than 1 meter!

Our initial work explored the possibility of using *device mobility* to emulate a virtually large antenna array [12]. This design uses the mobile device as a receiver (RX), with a decoupled transmitter (TX) either supported by infrastructure or "deployed" on-demand by the user (*e.g.*, mounted on another drone). By taking measurements of the reflected signals at multiple locations and applying the *Synthetic Array Radar (SAR)* algorithm [11], the system emulates the signals as if received from a large antenna array. Since 60GHz has a 5mm wavelength (12× shorter than WiFi/cellular), using 60GHz links can obtain high resolution with small movements [12].

Practical Limitations of SAR. Our goal is to design, build, and deploy an accurate mobile imaging system for practical applications. From experiments, we identified *two* fundamental limitations of SAR in real-world mobile settings. *(1)* SAR is highly sensitive to the RX trajectory tracking noise. Any deviation from the path produces significant error in the predicted points on the reflection surface, especially when the deviation is over RF wavelength. The movement deviations, however, are likely much greater than 60GHz's 5mm wavelength. *(2)* SAR imaging requires phase information ϕ. But any mm-level error in RX positioning creates large errors in ϕ. Thus phase offsets can largely affect SAR. Also, ensuring mm-level positioning and tracking is difficult using commodity hardware. Thus, accurate mobile 60GHz imaging requires a new approach robust to these errors.

II. RSS SERIES ANALYSIS (RSA)

We propose *RSS Series Analysis* (RSA), a more robust alternative that leverages 60GHz to identify the location, overall shape, size and material of the target object. Unlike SAR, RSA images an object using *only* RSS measurements along the receiver's trajectory. We summarize RSA here and detailed algorithms are in [13]. RSA offers two advantages over prior works on RF imaging [7], [12], [14]: *(1)* RSA can discover a rich set of objects properties at cm-level precision;

and *(2)* RSA is highly robust against device positioning and trajectory noise. Testbed results show that it can tolerate up to 10cm deviations without degrading imaging quality.

Our intuition is that the RSS measurements along a trajectory are highly correlated to the properties of a reflection surface. We verified this with 12 objects using a commodity 60GHz radio testbed. We also experimented with various movement patterns with deviations up to 10cm (noise). We observe that the *change* of RSS values at different measurement locations not only captures the overall object shape, but also tolerates errors in device positioning and tracking.

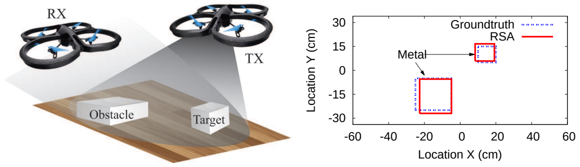
The core of RSA is to combine RX mobility with the high directionality of 60GHz beam-forming. Specifically, RSA treats each object surface as a continuous medium that reflects a directional 60GHz signal towards the directional RX. As RX moves and continually (re)aligns its beam to maximize RSS, we measure the RSS and its RX beam direction (*i.e.* angle of arrival (AoA)). By analyzing these *directional* RSS measurements, RSA sequentially recovers the important properties of the object: position, surface curvature, boundary and material:

1. Center position & surface curvature. Intuitively, the directional 60GHz signal propagates from TX to the object surface and to RX. We can estimate the object center location by intersecting TX main beam direction and the RX AoAs with the strongest RSS. For curvature, we compare the surface to a mirror. As it moves, the directional RX maximizes RSS by pointing the receive beam towards the mirror point of TX w.r.t. the object surface. This is a hypothetical point that would have originated the signals if there was no reflection, which can be computed as the intersections of the strongest RSS direction at each measurement location. With the locations of TX mirror point, object, and RX, we can derive the curvature radius based on the mirror and lens equation [15].

2. Surface boundary. Once curvature is determined, RSA detects surface boundary by exploiting the unique effect of 60GHz directionality on signal reflection. When RX is within the coverage of the reflected beam, the corresponding RSS is strong because RX can align its beam to capture the (strong) reflected signals. But when RX moves outside of the area, the quality of its beam alignment (and RSS) degrades quickly. Thus the shape of observed RSS values along RX trajectory is strongly correlated to the object boundary. Using the estimated surface curvature and center location, we can model this correlation to enable reliable detection of surface boundary.

3. Material. When a signal hits a surface, parts of it may be "absorbed," leading to a *reflection loss*. At 60GHz, this loss has a strong correlation of the surface material and the incident angle [16]. In particular, the RSS of a reflected signal is the RSS of a LoS signal (of the same propagation distance) minus the reflection loss (all in dB). Once we know surface location and curvature, we can derive the reflection loss and incident angle, and thus identify the likely surface material(s).

With multiple surfaces in presence, we can segment them based on the abrupt change of RX AoAs due to the change of TX mirror point. Then we apply RSA to each segment and derive their properties individually.



(a) Scenario setup (b) Imaging result (top view)

Fig. 1. "Realistic" case study of RSA imaging: a drone seeks to locate the small metal object while avoiding a nearby obstacle.

III. EVALUATION

We evaluate RSA in practical settings using off-the-shelf 60GHz radios. We experimented with 12 objects, each varying TX/RX position errors and RX trajectories (up to 10cm deviation). We observe that in presence of noise, RSA achieves cm-level accuracy across all objects, flat or curved. We also see that RSA can successfully narrow down the surface material.

As a case study, we consider the scenario in Fig. 1-a, emulated by two HXI horn antennas. The target rests on a wood floor with a nearby obstacle (metal, 18cm×18cm). With the help of another drone as TX, the RX drone first localize each other, and then coordinates with TX to sense the objects. Since the two objects are in proximity they can be covered by a single TX beam. After TX focuses its beam on the two objects, RX moves in two directions sequentially to determine location, curvature, width and height, and material. The visual result and the ground truth are shown in Fig. 1-b, where RSA recognizes two flat metal objects, their overall shape/size, and the wood floor in between.

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