60GHz Mobile Imaging Radar

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1. INTRODUCTION

Mobile computing is undergoing a significant shift right before our eyes. In the past, the user was the center of the mobile network, and her movements determined the operational properties of the mobile network. But this is changing with the arrival of autonomous mobile agents for a variety of applications. Today, semi-autonomous drones are carrying out military missions in lieu of manned-flights, while vacuum robots search for dirt in our homes. In the near future, intelligent cars will be fully in control of delivering us to our destinations, and first responder robots will be first on scene to find and rescue victims in disasters [15].

One of the critical challenges limiting the growth of these autonomous devices is the lack of accurate sensing systems, *e.g.* a mobile imaging radar system that captures the position, shape and surface material of nearby objects. These devices often operate in less than ideal sensing environments: at night or in dark rooms, or while moving at moderate speeds. Yet the desired level of accuracy is very high, and errors in sensing can produce dire consequences. For example, Google's self-driving cars are reported to use maps with inch-level precisions [18], while devices that assist the visually impaired must have errors smaller than 10cm [5, 11].

These constraints dramatically reduce the set of possible solutions. Traditional imaging systems rely on visible light imaging using cameras and object recognition. Unfortunately, they perform poorly in dark or low-light conditions, and lack the precision desired by these applications. Another approach relies on specialized hardware such as large lens radar for accurate signal detection and processing. But these devices are neither portable nor cost-effective for commodity devices. Finally, acoustic solutions have been used successfully for sensing over very short distances [24], but are easily disrupted by background noise and fail over longer distances.

60GHz Imaging Radar. An intriguing and still unexplored solution is a digital imaging radar system using reflective properties of narrow beamforming wireless links. A radar system using high frequency RF signals (e.g. 60GHz) has a number of key advantages over existing alternatives. First, 60GHz links are directional and highly focused, making them relatively immune to interference from environmental factors. Second, 60GHz beams exhibit good reflective properties, and work reliably regardless of lighting conditions under most indoor or outdoor conditions. Finally, 60GHz radios are relatively inexpensive, and small enough to be included in today's smartphones and tablets.

In this paper, we present early results in our efforts to design and evaluate a digital imaging radar system using reflections from 60GHz wireless beams. Such a system faces a fundamental challenge, that it is technically infeasible to build an accurate imaging radar using wireless hardware on a static mobile device. A simple rule from imaging radar theory [7], defined by eq.(1), holds for accuracy (radar resolution) and antenna size (aperture). For smartphone-sized antennas, even the most high frequency radios (5-120GHz) can produce resolutions no better than 1 meter, clearly insufficient for our needs.

$$Resolution = wavelength \times distance/aperture \quad (1)$$

Virtual Antenna Arrays. We take an alternative approach, by using user mobility to emulate a virtual antenna array with large aperture. Our design includes the user's mobile device as a receiver, with a decoupled transmitter either embedded in the infrastructure or "deployed" on-demand by the user (*e.g.* dropped by a drone). By taking measurements of the same reflected signal at multiple locations, we can emulate the signals received by different elements of a large antenna array. In addition, we can further improve the resolution of our "virtual antenna" using 60GHz transmissions. Since 60GHz has a carrier wavelength of 5mm (12x shorter than WiFi and cellular), using 60GHz links means a user can obtain fine-grain resolution with just small movements in the measurement area.

In the remainder of this paper, we present Nightcrawler, a 60GHz-based mobile radar system that leverages user mobility to emulate a large-aperture antenna array. We describe details of our design, including mechanisms for object detection, object imaging, and controlling precision. We present experimental results on a real 60GHz testbed, and show that we can achieve high precision ($\sim$1 cm) imaging with as little user movement as half a meter.

Our work is a promising first step in the development of high precision, wireless imaging radar systems. Initial results show promising accuracy, as well as added potential for using loss profiles to infer the *surface material* on detected objects. Ongoing work focuses on tolerating location errors for the transmitter, as well as extending imaging to multiple objects.

2. CONVENTIONAL VS. MOBILE RADAR

Before presenting our design of a high precision radar system, we need to first describe the principle and hardware requirements behind conventional imaging radars. We will then explain the dif-

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ferences between personal mobile radar systems and conventional imaging radar systems, and the challenges that arise as a result.

Traditional Radar Imaging. Imaging radars detect the presence, position, and shape of an object by emitting directional RF signals and capturing/analyzing the portion of signal reflected by the object. Specifically, a radar estimates its distance to the object by measuring the round trip time of the reflected signal, either directly using a highly precise clock, or indirectly by transmitting frequency modulation (FM) pulses and measuring the frequency offset of the reflected signal [7]. The radar also uses highly directional RF signals to "scan" the object. Because the signals reflected from the object and its nearby spaces carry different signal strengths, the radar can identify the object's position and shape with high precision. Finally, high-end radars can identify object material using dispersion analysis, where they emit RF signals at various carrier frequencies and collect reflection results. Since different materials have different reflection profiles across frequencies, one can estimate material type by analyzing reflection results.

Overall, traditional imaging radars have strong requirements on radio hardware, *e.g.* they require specialized FM circuits and highly directional dish antennas. These are easily met for applications where radar size and cost are not an issue, such as military radar systems or radio telescopes for use in astronomy.

Why Mobile Radar Imaging is Hard. Our goal in this paper is to design radar imaging systems to enable commodity mobile devices to recognize their surrounding environments. This is highly challenging, due to tight constraints on radio size, functionality and cost. *First*, the small form factor of mobile devices puts a hard limit on both antenna size (which determines aperture) and signal directionality. As shown by the Radar Theory in eq. (1), the small antenna size severely limits the maximum imaging resolution. For smartphone-sized antennas ($2.5cm$ aperture), the maximum imaging resolution for an object of $10m$ away is $1m$ using 120GHz transmissions or $24m$ at 5GHz. *Second,* today's mobile devices are not equipped with FM pulse circuits, which are required for distance estimation by traditional radar imaging. Adding such circuits would significantly increase costs for budget-conscious mobile radio chipsets. Similar cost constraints prohibit the inclusion of hardware solutions to perform dispersion analysis for material detection or clock-based distance computation[1].

3. 60GHZ IMAGING RADAR

To overcome challenges of size and cost in mobile devices, we propose to leverage human mobility to extend the reach of a single mobile antenna. We proposes *Nightcrawler*, a mobile radar imaging system using commodity 60GHz networking chipsets[2]. Using commodity chipsets, Nightcrawler performs object imaging using just signal measurements, and improves imaging resolution far beyond the theoretical limit defined by eq. (1). It achieves this by leveraging *user mobility* and unique RF propagation properties of *60GHz transmissions*. This section describes our core ideas and sets the context for details of our prototype in §4.

Leveraging 60GHz. Today's mobile devices are equipped with multiple wireless interfaces, *e.g.* cellular, WiFi, Bluetooth, and 60GHz radio [22]. We implement Nightcrawler using 60GHz radios because its unique propagation properties present three significant advantages for our application.

- 60GHz has a carrier wavelength of 5mm, more than 12x shorter than WiFi and cellular. According to eq. (1), the required antenna aperture for 60GHz is at least 12x smaller than WiFi/cellular for the same imaging resolution.
- 60GHz's short wavelength also makes its propagation much more stable/predictable. With minimum multi-path effects, signal strength remains stable over time, and is strongly correlated with propagation distance. This increases the robustness of our imaging design. For example, our imaging system can easily distinguish between a line-of-sight signal and a reflected signal that traveled over a longer distance, and use this fact to detect the presence of objects in local neighborhood.
- The object reflection profile is more stable at 60GHz. For example, the signal reflection loss has strong correlation with the object material. This enables Nightcrawler to narrow down the material type using signal strength measurements.

Mobility enabled virtual antenna array. Nightcrawler exploits the fact that as a user moves, her mobile device can take signal measurements at multiple locations, emulating a virtual antenna array whose antenna aperture is significantly larger[3]. This enables highly directional signal reception by a mobile device similar to those required by conventional radar imaging, and overcomes the limitation imposed by the size of mobile devices.

User mobility also increases the system's detection range and ability to detect surface curvature of objects. Surfaces with different curvatures reflect the signal to different directions in the space. Measuring reflections from different locations helps the radar capture the curvature of each of the object's multiple faces.

Decoupling transmitter and receiver. Given the small size of mobile devices, any mobile radar system cannot rely on just a single device to serve as both transmitter and receiver. Our design for a mobile radar system involves the primary mobile device, which acts as a receiver, and a decoupled transmitter, which can be either infrastructure-based, or a separate mobile device.

For example, an imaging system to assist the visually impaired may include an app on the user's smartphone, which coordinates with one or more transmitters embedded in the walls or ceiling. In contrast, an autonomous device (e.g. first responder robots) can "deploy" a secondary transmitter device.

Once deployed (or periodically for infrastructure devices), the transmitter (TX) sends 60GHz beacons that reflect off of nearby objects[4]. Each beacon includes the angle of transmission, and if possible the transmitter's location. Users hold a mobile device equipped with a 60GHz receiver (RX), and move in pedestrian speeds. Each RX periodically scans[5] and records signal strengths for beacons across different directions. Nightcrawler processes these data on the fly to identify, locate and image objects in the local area.

4. Nightcrawler: A FIRST LOOK

We now describe our initial design. Seen in Figure 1, a primary device (RX) and decoupled transmitter (TX) start from "sensing" mode to identify the presence of any object. Upon detection, they switch to "imaging" mode to build a physical map of the object(s). We assume that the RX knows its relative position from the TX.

4.1 Object Sensing

Nightcrawler devices sense objects using the bootstrapping procedure defined by IEEE 802.11ad, the standard for 60GHz trans-

[1]To measure round trip time accurately, *i.e.* with $1cm$ accuracy, the clock precision must be at least 0.033ns, which is extremely hard to realize on smartphones and laptops.

[2]Low-cost 60GHz chipsets are available today on the mass market, *e.g.* WiloCity chipsets cost $37.5 and has a $23m$ range [22, 26].

[3]Aperture of virtual array is equal to distance traveled by the user.

[4]The beacon transmitters rotate their beam direction periodically to cover multiple objects or larger objects.

[5]Today's 60GHz antenna arrays can adjust beam direction every $50us$. So each RX can scan multiple directions in real time.

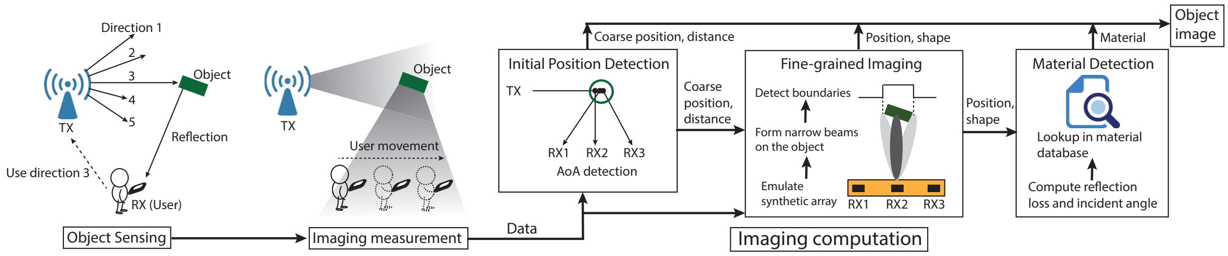


Figure 1: The high-level overview of the Nightcrawler radar imaging system.

missions [2]. The TX operates in the directional mode, steers its beam to different directions, *e.g.* in sectors of 3° in width, and embeds the direction in the signal. Operating in the omni-directional mode, the RX measures RSS and reports a list of TX beam directions where RSS exceeds the noise level[6]. The RX then identifies and removes from the list the set of TX beam directions whose transmissions did not experience any reflection. The remaining list of directions, if any, are those where the transmission was reflected, implying that at least one object exists in the local neighborhood.

To identify TX beam directions that did not experience reflection, the RX uses simple geometry to locate a set of candidate LoS beam directions based on the relative position of TX and RX and their antenna radiation patterns. It then validates each candidate direction by comparing its RSS to the model-predicted value without any reflection. If a direction gets (partially) reflected, its RSS will be lower than the model-predicted value due to longer propagation path and possible reflection loss.

4.2 Object Imaging

After detecting the presence of objects, Nightcrawler devices enter the "imaging" mode. Intuitively, Nightcrawler should use the above collection of "reflected TX beam directions" to drive imaging. That is, the TX focuses its transmissions on these directions (by rotating its beam repeatedly across them in a round-robin fashion) while the RX locates and images object(s) in each direction. To improve imaging efficiency, it is desirable to identify a subset of the directions that cover all the potential objects. In our preliminary work, we leave this optimization to future work and simply assume that the reflected direction set only has a single direction.

With this in mind, our following description on Nightcrawler assumes that during imaging, the TX focuses its beam on the targeted direction and transmits the same beacon signal repeatedly. The RX, while moving, operates in the directional mode and steers its beam around to capture signals at each measurement location. This is done using the *antenna alignment* procedure defined by 802.11ad – the RX steers its beam across various directions and reports the direction with the strongest RSS. Once the movement distance is sufficient, the RX executes the imaging algorithm on the measurement data to locate and image the object.

The Nightcrawler imaging algorithm includes three steps: (1) *coarse position estimation*, (2) *fine-grained imaging*, and (3) *material detection*. We now describe them in more details.

4.2.1 Coarse Position Estimation

Nightcrawler first estimates the object's relative position and distance to the RX. This narrows down the search space for the next step, which applies a more sophisticated approach to perform detailed imaging. The RX estimates the object position by extracting the angle of arrival (AoA) of the beacon signal. At each measurement location, Nightcrawler derives the AoA as the strongest receive beam direction. Since the TX embeds the beam direction in each beacon signal, the RX can estimate the object position as the intersection of the TX beam direction and the AoA.

Ideally, Nightcrawler should identify object position reliably from measurements at a single location. In practice, AoA detection can be noisy due to hardware artifacts, imperfect reflection from uneven surface, and the fact that each TX beam is not narrow enough. For example, our testbed results show that when using a TX beam of 10° beamwidth, the noise in AoA estimation can lead to up to $1m$ position error when the object is $6m$ away from the RX.

Nightcrawler overcomes this challenge by performing "majority vote" on measurements collected at multiple locations. Specifically, Nightcrawler considers data from N locations, each producing an estimated object position. It then identifies a cluster of $[N/2]+1$ positions with the minimum MSE among themselves, and computes the center of the cluster, *i.e.* the position with the minimum MSE to all the positions, as the final object position. This solution, while simple, can effectively improve the positioning accuracy. Our testbed results in §5 show that with N=9, the position error in the above example reduces from $1m$ to below $10cm$.

4.2.2 Fine-grained Imaging

This step derives the precise position and shape of the object by implementing a large aperture virtual antenna array from aggregating signal measurements at different locations. Specifically, Nightcrawler identifies the object shape by detecting its boundaries as well as surface curvature, *i.e.* flat, convex or concave.

Detecting Object Boundaries. Inspired by airplane radars that implement synthetic aperture radar (SAR) to detect object size [7], Nightcrawler uses a small and moving RX antenna to emulate elements of a large array. The resulting synthetic array has a very narrow beam pattern and can identify signals at fine-grained directions. Thus the RX can observe a sharp decrease in RSS along the object boundaries, and locate these boundaries with errors bounded by the (very narrow) beamwidth of the synthetic array.

A key component of our design is how to aggregate measured signals across locations to emulate the large array. This is done by "reverse-engineering" the process of a phased array focusing its beam. Specifically, let the estimated object position in the previous step be X_0. Nightcrawler picks a set of reflection "focus points" near X_0 as the potential boundary positions. Given a target image resolution r, any two neighboring focus points should be within a distance of $r/2$. For each focus point, Nightcrawler applies a *focus* process to derive the RSS of signals reflected by the small area of width r around the given focus point. This is done by first shifting the phase of signals collected at each measurement location by its distance to the focus point and then summing up all the signals across locations. After applying this on all the focus points, the RX obtains a reflected RSS map along the object itself. The object boundaries are the two focus points where the RSS drops sharply.

[6]This step is slightly different from 802.11ad where the RX only reports the direction with the strongest RSS.

Note that Nightcrawler emulates the large array without synchronizing TX and RX. This is because all the measurements are done by a single receiver RX. As long as the TX sends the same beacon signal (per TX beam direction) during imaging, the RX can eliminate any phase offset caused by differences in measurement time.

Inferring Surface Curvature. Nightcrawler recognizes the object's surface curvature based on a simple intuition – signals reflected by a flat surface display a standard sector shape that can be reconstructed based on the antenna pattern and the signal propagation distance, while signals reflected by a convex (concave) surface display a wider (narrower) sector shape. Driven by this intuition, Nightcrawler infers the surface curvature by the RX constructing the beam pattern of the received signal. Specifically, as the RX moves, it measures the RSS at different segment of the signal beam and aggregates them to build the received beam pattern.

While our first design of Nightcrawler identifies the type of surface curvature (flat/convex/concave), our ultimate goal is to discover detailed surface feature such as the curvature radius. This requires more sophisticated models on 60GHz signal reflection, which we leave to future work.

4.2.3 Material Detection

Finally, Nightcrawler infers the object material based on the RSS loss due to reflection. At 60GHz, the reflection loss correlates strongly with the material type and the incident angle. Existing measurements have built a comprehensive database on 60GHz reflection loss, covering 38 common materials and different incident angles [14]. Our own measurements on five different materials also align with existing findings.

The key element is to accurately determine the amount of RSS loss due to reflection and the reflection incident angle. To derive the reflection loss, Nightcrawler first computes the signal propagation distance (TX $\rightarrow$ object $\rightarrow$ RX) and applies the Friis free-space model to derive RSS without any reflection loss (RSS^*). It then subtracts from RSS^* the measured RSS value to derive the reflection loss. Computing the signal incident angle is easy given the relative position between TX and RX.

4.3 Imaging Overhead vs. Precision

Nightcrawler's imaging computation overhead is low. Our MATLAB implementation finishes in less than $15ms$ for all test cases. We expect that a good native C implementation on mobile devices should be comparable if not faster. Therefore, Nightcrawler's overall overhead and delay are dominated by its signal measurements.

Nightcrawler's measurement delay depends on user walking distance. The further the user walks, the larger the imaging delay. But user walking distance also directly affects the size (or aperture) of the synthetic array and thus imaging resolution. So there exists a tradeoff between imaging response time and resolution.

We should also pay attention to measurement frequency, *i.e.* the number of measurement locations for a given walk distance. Ideally we should minimize measurement frequency to save energy. However, since the number of measurement locations maps to the number of elements in the synthetic array, we need sufficient number of measurements to remove array artifacts such as side lobes. Our initial analysis suggests that for pedestrian speeds up to $1m/s$, the measurement frequency of 1 per $40ms$ (or 1 per $4cm$ movement) is sufficient to produce a high-quality synthetic array.

5. INITIAL FEASIBILITY STUDY

We perform initial evaluation on Nightcrawler using both testbed measurements and system simulations. We use commercial off-the-shelf 60GHz radios to conduct microbenchmark experiments on Nightcrawler, and to evaluate its end-to-end imaging performance under simple scenarios. We also run simulations to identify potential performance of Nightcrawler under general scenarios.


(a) (b) (c) (d) (e)

Figure 2: 5 different objects used in our testbed measurements.

5.1 Testbed Measurements

Our testbed consists of two HXI Gigalink 6451 60GHz radios,one as the transmitter (TX) and the other as the mobile receiver (RX). Compared with an ideal Nightcrawler system, the testbed has two hardware limitations. *First*, since there is no suitable 60GHz steerable antenna array on the market, we emulate beam steering by setting a horn antenna on a mechanical rotator and adjusting its beam direction in units of $0.5°$. This can provide accurate results because 60GHz signal strength is largely determined by directionality and signal patterns of the main beam lobe, and our horn antenna's main lobe pattern closely aligns with that of a 10x10 array [26]. Since 60GHz propagation is stable over time (verified by others [12, 25] and our own measurements), at each location the RX can accurately measure RSS across different directions despite its slower beam steering speed. *Second*, the HXI radio reports RSS without any phase information, so in the computation we set the phase of signals measured at all RX locations to the same value. This makes it difficult to perfectly focus the beam during boundary detection, and can potentially degrade the imaging performance.

Our experiments consider a simple scenario of object recognition. We place an object in the middle of a room. The TX is $2m$ away from the object and emits a fixed beam towards the object. The RX starts from an arbitrary location in the room, and as she walks around, Nightcrawler identifies the object position and shape. We test five objects with different size and surface curvature, shown in Figure 2. We also experiment with pedestrian users as objects. By default, the user walks $45cm$ and performs one RSS measurements every $1cm$. As mentioned earlier, we assume the RX knows her relative position to the TX.

Position & Distance Accuracy. We first examine the accuracy of the coarse position detection described in §4.2.1 with $N = 9$. Table 1 lists errors in estimated position, distance and surface orientation when the RX is $3m$ away from the object. Across the five different objects, the position offset ranges between $1.7cm$ and $12cm$ while the distance offset is even smaller ($< 0.4cm$)[7]. This translates into less than $1°$ orientation error. Furthermore, we observe that the accuracy is higher for objects with planar surfaces, compared to those with convex surfaces. This is because signals reflected by convex surfaces become more scattered compared with planar surfaces, leading to larger variance in estimated reflection points. We also repeat the experiments by varying the RX to object distance between $2m$ and $6m$ and obtain similar results. Overall, Nightcrawler achieves an 10cm-level accuracy which should be sufficient for most mobile applications.

Boundary Detection Performance. Table 2 lists the performance of Nightcrawler's boundary detection in terms of the off-

[7] The distance offset is the projection of the position offset along the line of object$\rightarrow$RX.

Objects in Figure 2	Position offset	Distance offset	Orientation error
(a) Desktop (Metal)	1.7cm	0.1cm	0.2°
(b) Monitor (Plastic)	6.9cm	0.1cm	0.6°
(c) Board (Wood)	5.5cm	0.1cm	0.5°
(d) Convex Box (Plastic)	12.3cm	0.4cm	1.0°
(e) Cylinder (Metal)	10.4cm	0.3cm	/

Table 1: Performance of Nightcrawler's Position Estimation.

Object Width (Material)	Object-RX distance		
	3.5m	4.8m	6m
24.5cm (Metal)	1.5cm	3.0cm	3.0cm
26cm (Plastic)	4.0cm	5.0cm	4.5cm
22cm (Wood)	4.0cm	4.0cm	4.5cm

Table 2: Accuracy of Nightcrawler's boundary detection, in terms of the offset in detected object width.

set in object width. Here we compare three objects of similar size but different materials. Despite the lack of phase information, Nightcrawler already achieves $5cm$ and less error in object width estimation. Later in §5.2 our simulation result confirms that when phase information is available, the error in width detection is cut in half. In addition, we also observe that the width accuracy for the metal object is slightly better than those of the plastic and wooden objects. This is mostly because the smoother metal surface enables stronger signal reflection. Finally, we see that the closer the user (RX) is to the object, the more accurate the imaging. This aligns with the Radar Theory in eq.(1) as well as the common expectation on imaging – as a user gets closer, she sees the object more clearly.

End-to-end Imaging Results. By combining the results on position, boundary and surface curvature, Nightcrawler can produce a detailed map of the object surface. Figure 3 plots the imaging result of a metal object at different user-to-object distances. The thin blue dash line in Figure 3(b)(c) marks the true object shape, while the thick black line is the imaging result of a surface. We see that Nightcrawler can identify the physical surface almost perfectly. Notice that in this example the user's walking path is in parallel with the TX transmitting direction. This is not necessary. In our experiments, the walking direction does not affect the results much as long as the path is relatively straight. It is the user-to-object distance and walking distance that matter the most.

Tracking Moving Pedestrian. We also evaluate Nightcrawler when the object is a moving pedestrian traveling at 1m/s towards the RX (see Figure 4). Here the RX user travels $0.8m$ in total during imaging. In the first $0.4m$, the RX detects a human $2.3m$ away (with a $6.9cm$ offset); in the second $0.4m$, the human is $1.5m$ away and the position offset reduces to $0.27cm$. This preliminary result shows that Nightcrawler can potentially identify and track moving pedestrian using signal reflection.

5.2 Simulation Results

We perform simulations to examine Nightcrawler in absence of testbed artifacts. Our simulation reproduces the scenario in Figure 3(a). The metal object surface is represented by dense discrete points and does not introduce any reflection loss. The propagation follows the Friis free-space model for 60GHz transmissions.

Is phase information beneficial? Figure 5(a) compares the imaging error on object width with and without phase information. The simulation results without phase information are similar to our testbed measurements. When phase information is available, Nightcrawler's error reduces by 50%. Therefore, a practical implementation of Nightcrawler can benefit significantly from obtaining signal phase information from the underlying 60GHz chipset.

Impact of array elements. Due to cost and sizing limits, mobile 60GHz chipsets are likely to use small number of array elements, *e.g.* the Wilocity chipset has a 2×8 array, which leads to weaker directivity. We compare Nightcrawler performance using different arrays with 2×8, 6×6 and 10×10 elements, and found that they perform similarly if signal phase information is available.

Impact of object size. We examine a broad range of object sizes between $5cm$ and $1m$, and vary the user walk distance between $0.5m$ and $1m$. Our results, omitted for brevity, show that the absolute imaging error is independent of the object width, as long as the object is not too wide so that its edges fall out of the scope of a single 60GHz beam. To cover these objects, Nightcrawler needs to rotate the TX beam during the measurement process (see §4.1).

How far should users walk? Nightcrawler seeks to achieve high-resolution imaging by a user walking a short distance. Figure 5(b) plots the required walk distance vs. the resulting width error under different user-to-object distances. Since the virtual antenna aperture scales with the walk distance, it is no surprise that the further the user walks, the higher the accuracy is. A practical implementation of Nightcrawler should exploit this tradeoff to achieve robust, efficient and high responsive object imaging. Overall, the result is very encouraging – even when the user is $8m$ away from the object, traveling just $1m$ can achieve $2cm$ imaging accuracy.

6. RELATED WORK

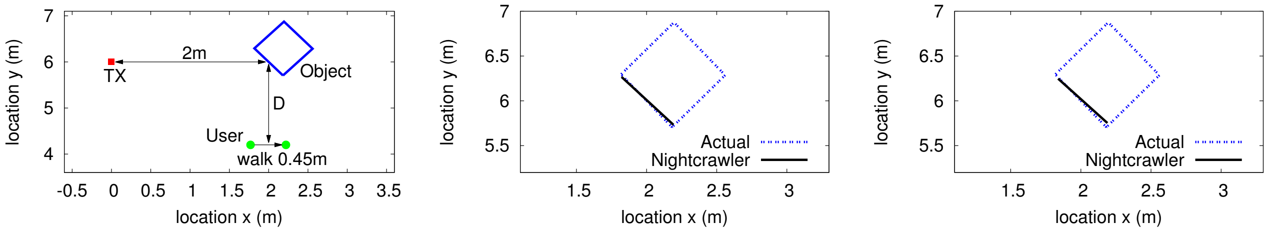
Sonar and Radar Systems. Sonar and radar systems are deployed to detect the speed and position of moving targets, or to measure the contour of the terrain [21]. Portable radar devices are available to detect concealed weapons in airports [10]. To provide high-resolution imaging, these systems require either special hardware, *e.g.* X-Ray or lenses too large for mobile devices [23]. Different from existing works, Nightcrawler achieves high-resolution imaging using 60GHz networking chipsets that are being integrated into today's mobile devices. While our design is inspired by the SAR method used by airplane radars [7], our key contributions include the novel application of the SAR concept to mobile 60GHz scenarios and the detailed system design and experimentation.

Camera-based Systems. Many have developed image-based object recognition systems [9, 16, 17]. These methods, however, cannot accurately measure distance between user and object. Google's Project Tango [1] detects an object's position and shape using three bulky cameras, including an infrared depth camera and a fish-eye lens. Yet it only works in environments with good visibility, and cannot reliably identify object material. Nightcrawler overcomes these challenges by leveraging 60GHz networking chipsets in mobile devices. We show that reflections of 60GHz signals can reveal key physical properties of the object surface even without any light.

RF-based Systems. Recent works on WiFi-based systems [4, 3, 8, 19] target coarse-grained human or object tracking, *e.g.* detecting relative movement of human body, recognizing predefined user gestures [20], or scanning tumors or weapons on human body [6]. Nightcrawler differs from these works by performing detailed imaging on objects, including its shape, surface curvature and material. Nightcrawler chooses 60GHz as the underlying RF technology because compared with WiFi, 60GHz offers much smaller wavelength and much more stable (and predictable) signal propagation. This largely boosts the imaging performance, enabling Nightcrawler to identify, locate and image various objects with high precision.

7. OPEN CHALLENGES

We present the initial design of Nightcrawler, a 60GHz imaging radar that locates and images objects in local neighborhood.



(a) Imaging Setup (b) $D = 3.5m$ (c) $D = 6m$

Figure 3: Testbed results: Nightcrawler images a metal object when varying the user-to-object distance D.

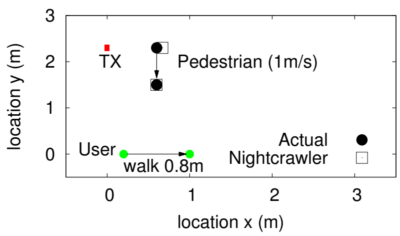
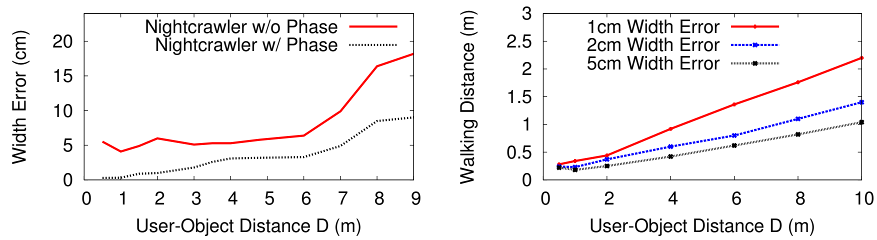


Figure 4: Testbed results: Nightcrawler detects and locates a pedestrian user.



(a) Benefits of phase information (b) How Far Should User Walk?

Figure 5: Simulated Nightcrawler radar imaging results for a metal object.

Our initial evaluation under simple scenarios confirms the feasibility of Nightcrawler in performing high-resolution object imaging. As ongoing work, we seek to improve and further experiment on Nightcrawler. In particular, we consider the following directions.

Handling device positioning errors. Our basic design assumes the RX knows her position to the TX and tracks her position precisely when walking. In practice, any positioning error translates into inaccurate phase shifts during boundary detection (see §4.2.2), and can largely affect imaging performance. Addressing this challenge requires mechanisms for reliable ranging and motion tracking (*e.g.*[13]) and those for identifying and correcting phase errors.

Identifying curvature details. We take a data-driven approach to extract surface curvature details – collect a large measurement on different surfaces, identify key features and then develop efficient classification algorithms.

Imaging multiple objects. When multiple objects are in range, Nightcrawler can potentially image them simultaneously. Doing so requires the RX to first narrow down a subset of "reflected TX beam directions" that cover all the objects (see §4.2.2). The TX then beams along these subset of directions during the imaging measurement process.

8. REFERENCES

[1] `https://www.google.com/atap/projecttango`.

[2] IEEE 802.11 Task Group AD. `http://www.ieee802.org/11/Reports/tgad_update.htm`.

[3] ADIB, F., KABELAC, Z., KATABI, D., AND MILLER, R. C. 3d tracking via body radio reflections. In *Proc. of NSDI* (2014).

[4] ADIB, F., AND KATABI, D. See through walls with wi-fi! In *Proc. of SIGCOMM* (2013).

[5] AL-SALIHI, N. Precise positioning in real-time for visually impaired people using navigation satellites. *International Journal of Engineering and Technology 12*, 2 (2010), 83–89.

[6] BHARADIA, D., JOSHI, K. R., AND KATTI, S. Full duplex backscatter. In *Proc. of HotNets* (2013).

[7] CHAN, Y. K., AND KOO, V. C. An introduction to synthetic aperture radar (sar). *Progress in Electromagnetics Research B* (2008), 27–60.

[8] CHETTY, K., ET AL. Through-the-wall sensing of personnel using passive bistatic wifi radar at standoff distances. *Trans. on Geoscience and Remote Sensing 50*, 4 (2012).

[9] DAVISON, A. J., ET AL. Monoslam: Real-time single camera slam. *Trans. on Pattern Analysis and Machine Intelligence* (2007).

[10] FEDERICI, J. F., ET AL. Thz standoff detection and imaging of explosives and weapons. In *Proc. of Defense and Security* (2005).

[11] GUERRERO, L. A., VASQUEZ, F., AND OCHOA, S. F. An indoor navigation system for the visually impaired. *Sensors 12* (2012).

[12] HALPERIN, D., ET AL. Augmenting data center networks with multi-gigabit wireless links. In *Proc. of SIGCOMM* (2011).

[13] KUMAR, S., ET AL. Accurate indoor localization with zero start-up cost. In *Proc. of MobiCom* (2014).

[14] LANGEN, B., LOBER, G., AND HERZIG, W. Reflection and transmission behavior of building materials at 60ghz. In *Proc. of PIMRC* (1994).

[15] LINE, M. Robot rescue: First-responders of the future. FoxNews.com, June 2014.

[16] LOWE, D. G. Object recognition from local scale-invariant features. In *Proc. of ICCV* (1999).

[17] LOWE, D. G. Distinctive image features from scale-invariant keypoints. *International journal of computer vision 60*, 2 (2004).

[18] MADRIGAL, A. C. The trick that makes google's self-driving cars work. The Atlantic, May 2014.

[19] MOSTOFI, Y. Cooperative wireless-based obstacle/object mapping and see-through capabilities in robotic networks. *IEEE TMC* (2013).

[20] PU, Q., ET AL. Whole-home gesture recognition using wireless signals. In *Proc. of MobiCom* (2013).

[21] SCHEER, J. A., AND MELVIN, W. L. *Principles of modern radar*. The Institution of Engineering and Technology, 2013.

[22] SHANKLAND, S. Wilocity: 2015 phones getting extra-fast 802.11ad networking. CNet, February 2014.

[23] TSENG, T.-F., ET AL. High-resolution 3-dimensional radar imaging based on a few-cycle w-band photonic millimeter-wave pulse generator. In *Optical Fiber Communication Conference* (2013).

[24] ZHANG, Z., ET AL. Swordfight: Enabling a new class of phone-to-phone action games on commodity phones. In *Proc. of MobiSys* (2012).

[25] ZHOU, X., ET AL. Mirror mirror on the ceiling: Flexible wireless links for data centers. In *Proc. of SIGCOMM* (2012).

[26] ZHU, Y., ET AL. Demystifying 60ghz outdoor picocells. In *Proc. of MobiCom* (2014).