SquiggleMilli: Approximating SAR Imaging on Mobile Millimeter-Wave Devices

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https://github.com/hregmi77/SquiggleMilli
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Number of 5G subscriptions in North America from 2018 to 2026 (in millions)

5G subscriptions in North America 2018-2026

Source: Statista
What Is 5G And Mmwave?

mmWave Technology

Airport Security Scanner

Remote Sensing

Telecommunications
Can we bring these functionalities to commodity 5G smartphones?

Behind Wall Detection

Packaging and Inventory

Airport Contra-band Scanner

mmWave antenna
SquiggleMilli

Squiggle motion path

Virtual Grid
Drawn by User

Object of Interest

Pistol inside bag
SquiggleMilli

Actual Object

What vision camera produces

What SquiggleMilli produces
SquiggleMilli

What vision camera produces

Actual Object

What SquiggleMilli produces
Constructing Millimeter-Wave Image
Constructing Millimeter-Wave Image

3D Spectrogram

Y

X

10
From Measured Signal to Image

FFT (t) → FFT2D (x, y) → p(t)*

FFT: Fast Fourier Transform
IFFT: Inverse Fast Fourier Transform

IFFT3D (x, y, z)

Camera image → 3D mmWave image
Challenges

Hand-held imaging
- Non-linear motion
- Non-Uniform Sampling
- Multiple Objects

Specularity and weak reflectivity
SquiggleMilli Overview

Squiggle Correction and Objects Extraction

- Reflected Signals & Squiggle Aperture Locations
- Non-linear Motion Compensation
- Missing Grid Locations Recovery
- Multi-Focusing & Voxel Segmentation

Full Shape Recovery and Automatic Classification

- Trained Generator & Discriminator
- Quantifier
- Classifier
- 2D Object Shape, 3D Features, & Class
Challenges

- Hand-Held Imaging
- Specularity and Weak Reflectivity
Challenges

Hand-Held Imaging

Specularity and Weak Reflectivity
Non-linear Motion

Squiggle Grid

Ideal Grid
Motion Error Compensation

Phase Correction: \( d_{u2} \exp(jk2(d_u - d_s)) \)

Multi Point Reflectors

\[
\begin{align*}
\min & \sum_{i \in N, j \in N, i \neq j} \left| s_u^i(x_u, y_u, \omega) - s_u^j(x_u, y_u, \omega) \right|_{k=\omega/c} \\
\text{s. t.} & \quad |d_u - d_s| < \lambda/2
\end{align*}
\]
Missing Samples

More than 50% samples are missing
Missing Samples Recovery

Motion Corrected Samples  \[\rightarrow\]  Standard Compressed Sensing (CS) Technique  \[\rightarrow\]  Recovered Samples

CS Customization

- Compressed Sensing fails if data are correlated and wide
- Visual-aid ensures randomness in data points collected
- We also limit the range to 4 m to avoid wide problem as our application is targeted for short range
- Additionally, we use Density based clustering algorithm (DBSCAN) to separate objects in the scene
Challenges

- Hand-Held Imaging
- Specularity and Weak Reflectivity
Specularity And Weak Reflectivity

Object surface acts like mirror and transmitted signal bounces off an angle it will not come back to the receiver.
Motivation To Use Machine Learning

3D mmWave Image

Ground-Truth Image

Conditional Generative Adversarial Networks (cGAN)

Epoch: 1

Difficult to Recognize Shape
Motivation To Use Machine Learning

3D mmWave Image

Ground-Truth Image

Conditional Generative Adversarial Networks (cGAN)

Epoch: 10

Learning real image distribution
Motivation To Use Machine Learning

Conditional Generative Adversarial Networks (cGAN)

Epoch: 1000

3D mmWave Image

Ground-Truth Image

Shape Fully Recovered
Motivation To Use Machine Learning

3D mmWave Image

Generator

Post Training

Object is human perceptible
Shape Recovery With SquiggleMilli
Implementation

mmWave Hardware
- Start Frequency: 77.33 GHz
- Effective BW: 3.22 GHz

Co-located mmWave hardware and AR Camera
Implementation

Squiggle Pose Collection

Squiggle motion path

Virtual Grid Drawn by User

Object of Interest
Real Data Collection

- Volunteers are asked to squiggle phone to collect pose data
- Then, we place mmWave in precise mechanical controller
- It scans the area of 20 x 20 cm²
- Apply pose to obtain the squiggle data set

- To collect ground-truth 2D shape, we use co-located AR device
- MmWave 3D image: 40x1000x236 => 32x64x96
- 2D shape ground-truth: 128x256 depth image
- Takes ~ 15 mins/sample

2918 LOS and NLOS Real Samples

Real data collection is slow and ML needs lots of data, what can we do?
Data Collection

Synthetic Data Generation

- Large data scales for mmWave are not available
- We collected multiple 3D shapes from ShapeNet
- We projected the image into 2D shape and apply different 3D rotation matrix to generate 3D voxel
- 3D voxel is then used in Ray Tracing Algorithm
- Introduced various noises in simulation
- It generates the mmWave image like the images generated by SAR Imaging Devices
- Single simulation takes ~ 1.5 min in our PC (Intel Xeon @ 32 GB RAM)

9800 Synthetic Samples
Evaluation

Hand-Held Imaging

Specularity and Weak Reflectivity
Evaluation

Hand-Held Imaging

Specularity and Weak Reflectivity
Hand-held Imaging

**Motion Correction**

Shape quality improved ~4 times

**CS Recovery**

Scan Requirement Reduced by 30 times
Evaluation

- Hand-Held Imaging
- Specularity and Weak Reflectivity
Full Shape Recovery With SquiggleMilli

Human perceptible shape generated by Generator
Full Shape Recovery With SquiggleMilli

Median similarity to ground-truth is 90% for NLOS

LOS: Line of Sight
NLOS: None Line of Sight
Unseen: Objects not included in Training but looks like the Category of objects trained

SSIM: SquiggleMilli
SSIM: Traditional SAR
Object Classification

Objects are selected which are used in TSA Screening

Objects are correctly classified to respective classes

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<th>Boxcutter</th>
<th>Cellphone</th>
<th>Explosive</th>
<th>Hammer</th>
<th>Knife</th>
<th>Pistol</th>
<th>Scissor</th>
<th>Screw</th>
<th>Other</th>
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Field Trials

Human perceptible shape even when object is occluded
Field Trials

Achieved 72% shape similarity with just 3.2 pts/cm² scan density
Conclusion

❑ SquiggleMilli brings high-resolution, through-obstruction imaging into cheap, ubiquitous mobile devices

Thank you!

Please check out our paper for more results: https://github.com/hregmi77/SquiggleMilli

Any Questions: Please email to hregmi@email.sc.edu