MilliCam: Hand-held Millimeter-Wave Imaging

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https://cse.sc.edu/~sur/
Key enabling technology: Millimeter-wave

190 Million subscribers

~7x

1.3 Billions

1.9 Billions

10x increase in 5G subscriptions within the next 4 years

Source: Statista, 2020 - 2024
Opportunity for New Internet of Things Applications

Detecting finger movement

Monitoring vital signs

Enabling sports analytics

Imaging concealed objects
Imaging Concealed Objects: Applications

- Contra-band detection
- Moisture detection
- Hidden structure detection
- Inventory counting, Missing/damaged items detection
- mmWave antenna

Contra-band detection
Imaging Concealed Objects: Applications

Can we bring these functionalities to commodity 5G smartphones?

- Moisture detection
- Inventory counting, Missing/damaged items detection
- Contra-band detection
Constructing Millimeter-Wave Image

$\sigma_1$  

$\sigma_2$  

$\sigma_n$  

$p(t)$  

Reflected signals

mmWave antenna
Constructing Millimeter-Wave Image

Time (t)

Space (u)
From Measured Signal to Image

Time (t) → FFT (t) → FFT (u) → X → IFFT (t,u) → mmWave image

FFT: Fast Fourier Transform
IFFT: Inverse Fast Fourier Transform

Camera image → mmWave image

FFT: Fast Fourier Transform
IFFT: Inverse Fast Fourier Transform

Camera image → mmWave image
Challenges

Hand-held motion error

Unknown object location
Challenges

Hand-held motion error

Unknown object location
Hand-held Motion Error

Controlled movement-based mmWave image

Hand-held mmWave image
Error Correction for Hand-held Imaging

\[
\text{Camera image} \xrightarrow{\text{FFT (t)}} \text{FFT (t)} \xrightarrow{\text{FFT (u)}} \text{Error (e)} \xrightarrow{p(t)^*} \text{IFFT (t,u)} \xrightarrow{\text{Error-corrected image}} \text{Hand-held image}
\]
Challenges

- Hand-held motion error
- Unknown object location
Challenges

- Hand-held motion error
- Unknown object location
Unknown Object Location

Known object location

Unknown object location
De-focused Image with Unknown Location

Camera image

mmWave image with unknown object location

Image with known object location
Autofocusing with Unknown Object Location

mmWave imaging with hand-held error correction centered at \((X_C, Y_C)\)

Image center \((X_C, Y_C)\)
Auto-focusing with Unknown Object Location

mmWave imaging with hand-held error correction centered at \((X_C, Y_C)\)

Image center

\((X_C, Y_{new})\)
Auto-focusing with unknown object location

mmWave imaging with hand-held error correction centered at \((X_C, Y_C)\)

New \((X_C, Y_C)\)

Image center
Autofocusing with Unknown Object Location

mmWave imaging with hand-held error correction centered at \((X_C, Y_C)\)

New \((X_C, Y_C)\)

Image center

PSNR improvement \(> 3\) dB?

PSNR: Peak Signal-to-Noise Ratio
Autofocusing with Unknown Object Location

mmWave imaging with hand-held error correction centered at \((X_C, Y_C)\)

New \((X_C, Y_C)\)

Image center

PSNR improvement > 3 dB?

PSNR: Peak Signal-to-Noise Ratio
Autofocusing with Unknown Object Location

mmWave imaging with hand-held error correction centered at \((X_C, Y_C)\)

New \((X_C, Y_C)\)

Image center

PSNR improvement > 3 dB?

PSNR: Peak Signal-to-Noise Ratio
Autofocusing with Unknown Object Location

mmWave imaging with hand-held error correction centered at \((X_C, Y_C)\)

PSNR improvement > 3 dB?

PSNR: Peak Signal-to-Noise Ratio
Hand-held Experimental Platform

- Intel Galileo IoT platform + Qualcomm IEEE 802.11ad
- 64 beams at 60 GHz
- 2 GHz channel bandwidth
  == 0.5 ns timing resolution
- A repurposed off-the-shelf communication device
Shape Discrimination
Shape Dimensions Estimation

Error (%) vs True dimensions of the objects (Area & Avg. of length and breadth):
- 5x5 cm²
- 10x10 cm²
- 20x20 cm²
- 20x30 cm²
- 30x20 cm²
Imaging Multiple Objects

Gap: 13 cm

20 cm

15 cm

2 m
Imaging More Complex Object

Camera image

mmWave image
# MilliCam summary

## Potentials and challenges of hand-held mmWave imaging

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<td>*</td>
<td>Wide-bandwidth and small wavelength at millimeter-wave enable high precision see-through imaging.</td>
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<td>But, hand-held motion error and unknown object location can affect the image quality severely.</td>
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## System summary

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<td>MilliCam employs sensor-based error correction and iterative autofocusing to overcome the challenges.</td>
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<td>MilliCam is a first-of-a-kind system to enable high-quality see-through imaging on 5G devices.</td>
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