UbiComp / ISWC 2024

Wi-Painter: Fine-grained Material Identification and Image Delineation Using COTS WiFi Devices

Dawei Yan[1], Panlong Yang[2], Fei Shang[1], Weiwei Jiang[2], Xiang-Yang Li[1]

[1] University of Science and Technology of China

[2] Nanjing University of Information Science & Technology

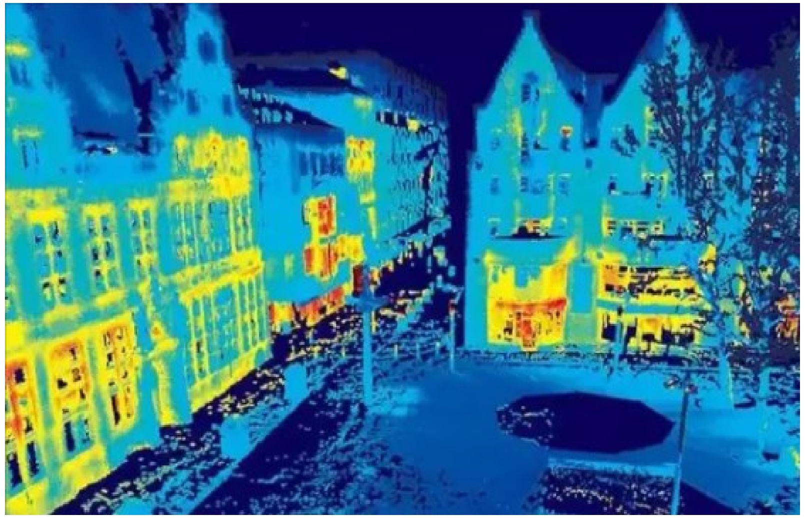
2024-10-8

Applications of Material and Shape Sensing

Deep sensing of the material and shape of objects in the environment can provide opportunities for many applications

Airport Security Check

Express Package Check



Indoor Mapping

Flaws of Existing Technologies

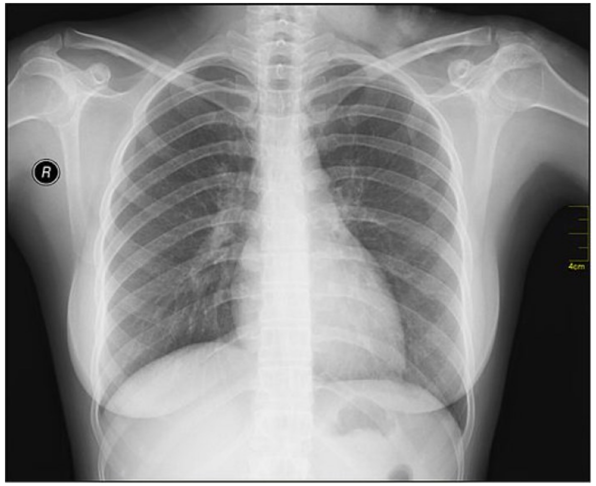
◆ **RGB-based**

- ✓ Sensitive to light
- ✓ Cannot see through the interior
- ✓ Poor effect on similar materials

◆ **Infrared-based**

- ✓ Low resolution
- ✓ Sensitive to ambient temperature
- ✓ Poor effect on transparent materials

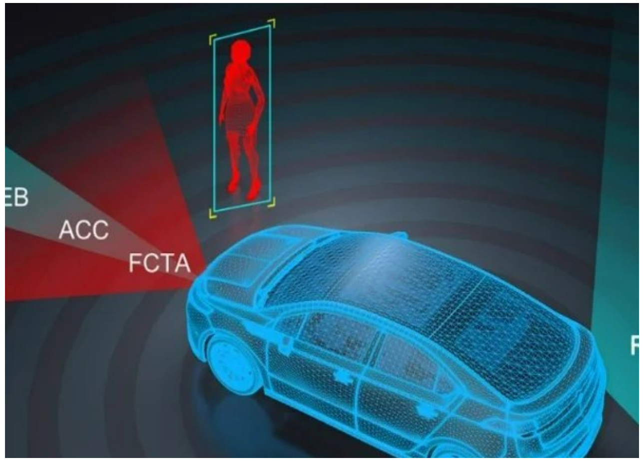
◆ **X-Ray-based**



- ✓ Specialized and expensive equipment
- ✓ High data processing and storage costs
- ✓ Slow speed

Flaws of Existing Technologies

◆ Radar-based



- ✓ Limited sensing range
- ✓ Relatively high equipment cost

◆ SDR-based

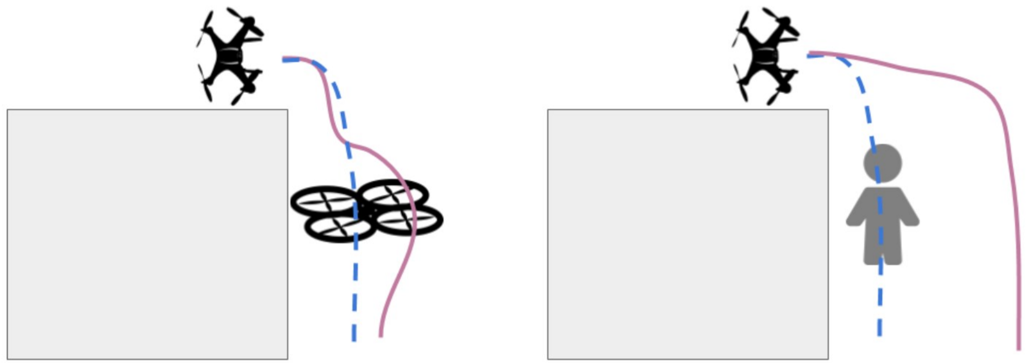
- ✓ Specialized and expensive equipment
- ✓ High data processing and storage costs
- ✓ Slow speed

◆ RFID-based

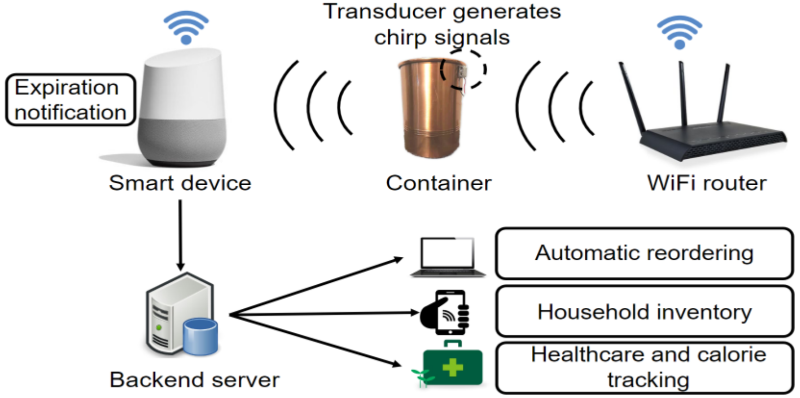
- ✓ Low resolution
- ✓ Limited sensing range
- ✓ Sensitive to metals and liquids

WiFi-based Methods Expand Opportunities

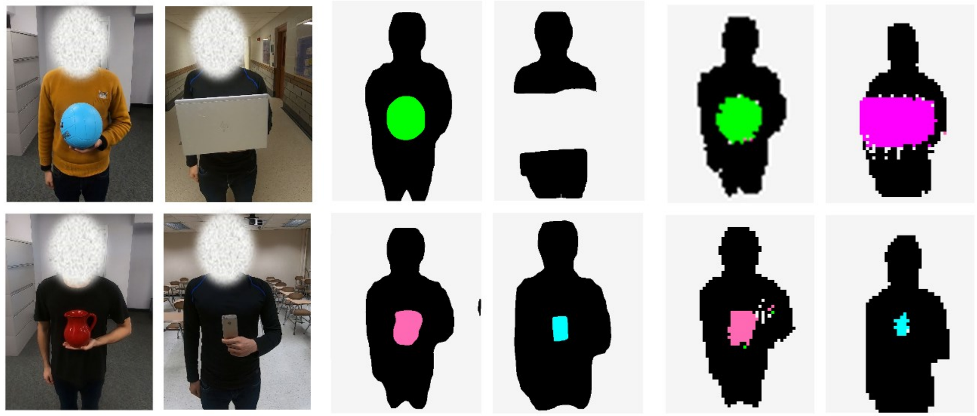
In recent years, some works have used COTS WiFi devices to achieve material identification and object imaging



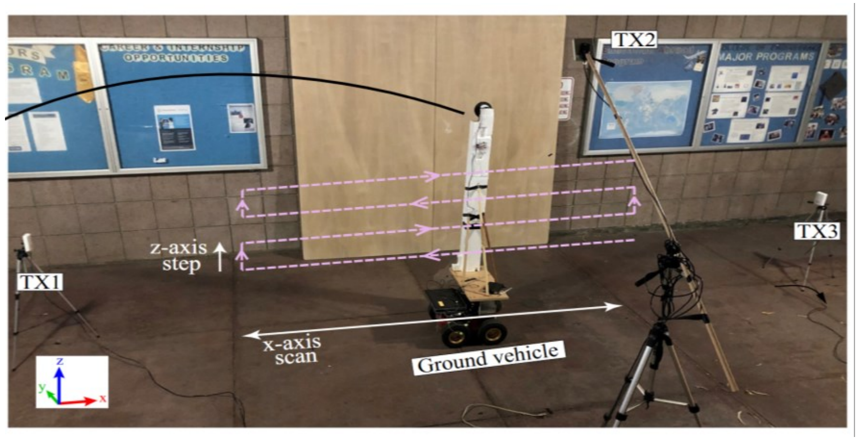
✓ IntuWition (MobiCom 2019)



✓ LiquidSense (UbiComp 2020)



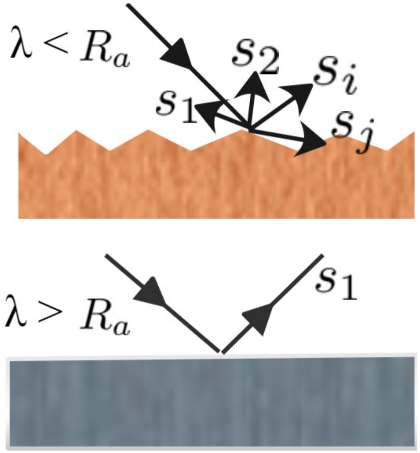
✓ WiSIA (SenSys 2020)

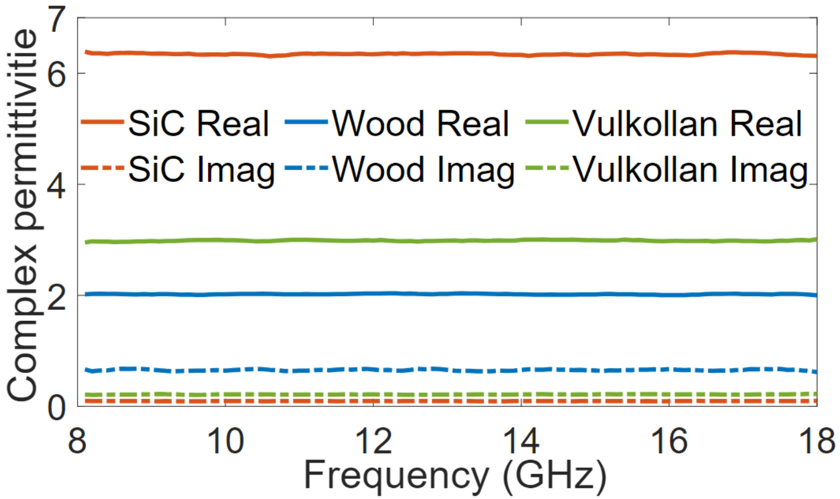


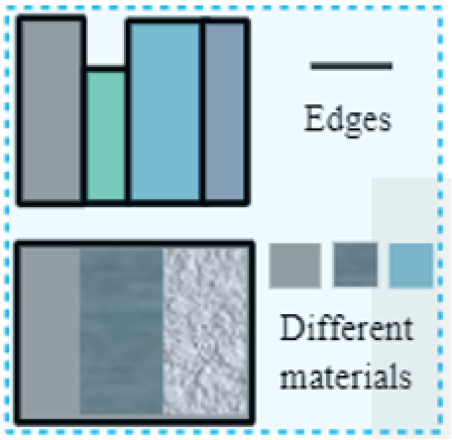
✓ Wiffract (MobiCom 2022)

Limitations of Existing WiFi-based Methods

However, there are still major limitations when facing some practical targets (e.g., smooth surfaces, solids, complex structures).







✓ **Less backscattering features**: At low frequencies, specular reflections (bottom) rather than diffuse reflections (top)

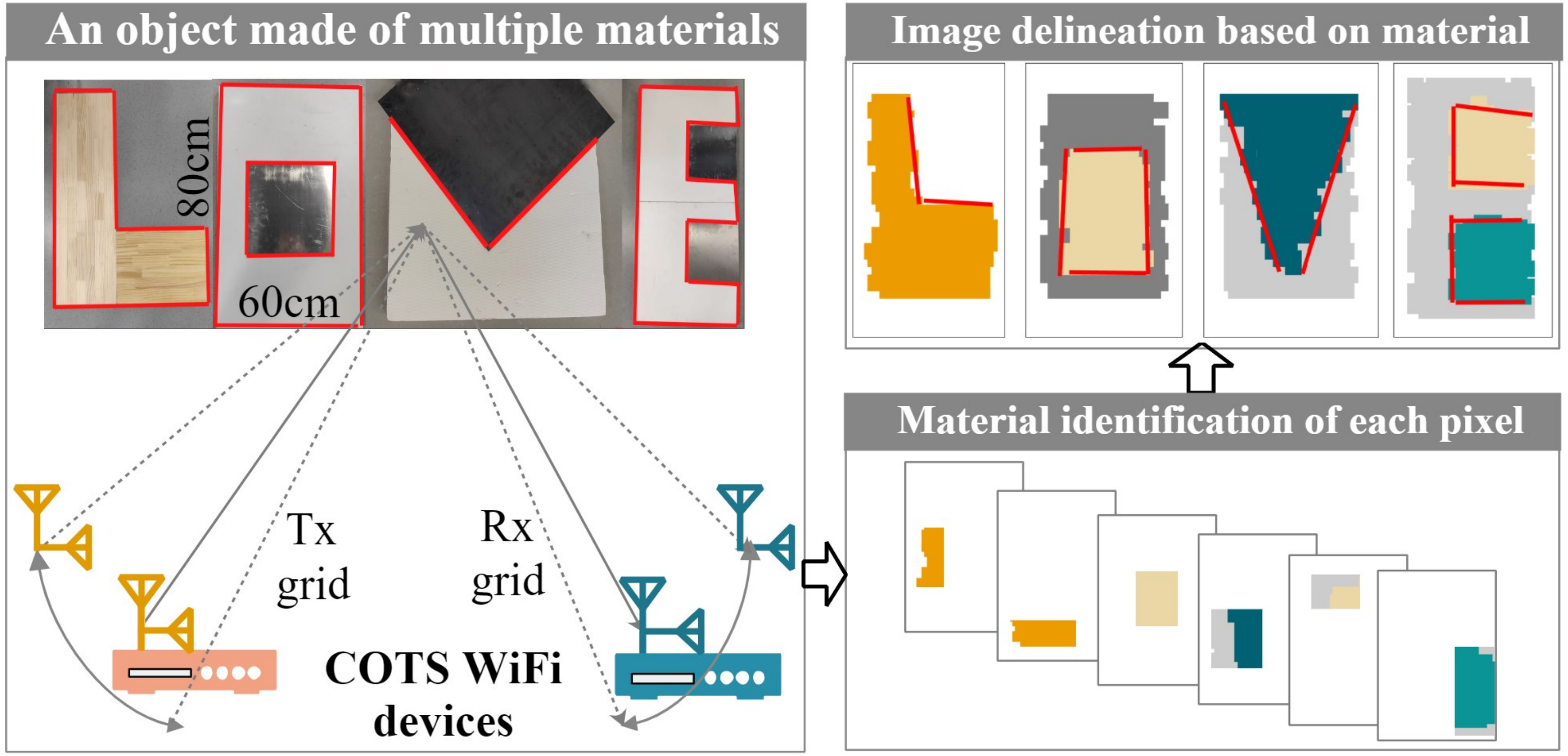
✓ **Less frequency features** : The complex dielectric properties of most solid materials are not frequency sensitive

✓ **Internal component**: Most solutions do not consider that an object is composed of different materials.

Our Solution: Wi-Painter

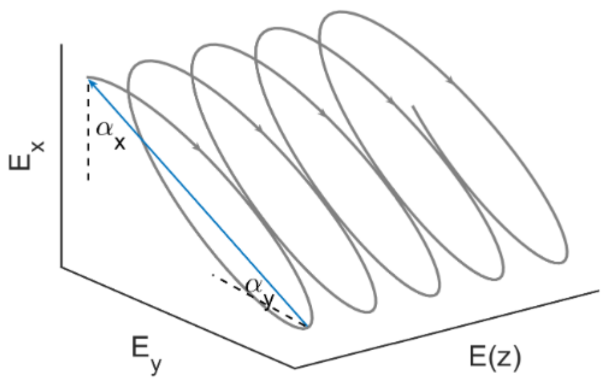
We propose Wi-Painter:

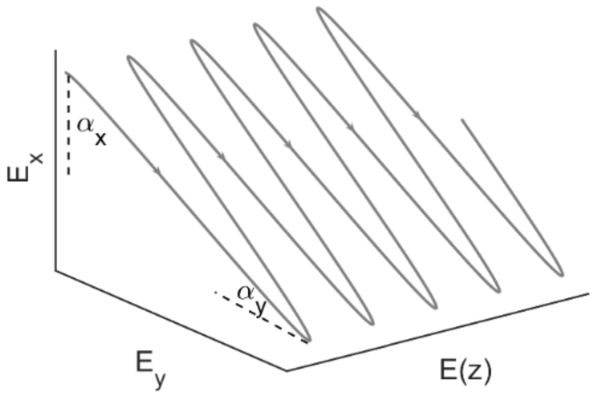
- ✓ Fine-grained material identification and imaging
- ✓ No prior data of the target materials
- ✓ No high-bandwidth scans with WiFi devices

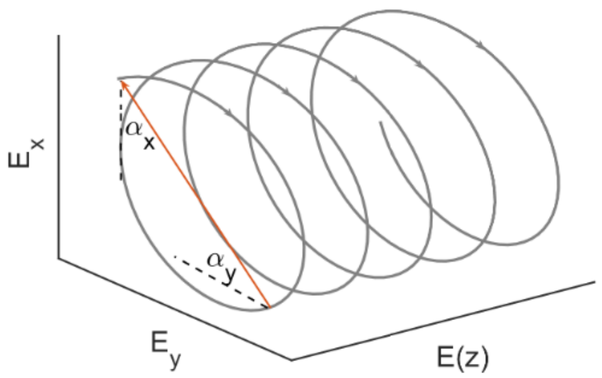


Basic Idea

Propagation of polarized electromagnetic waves



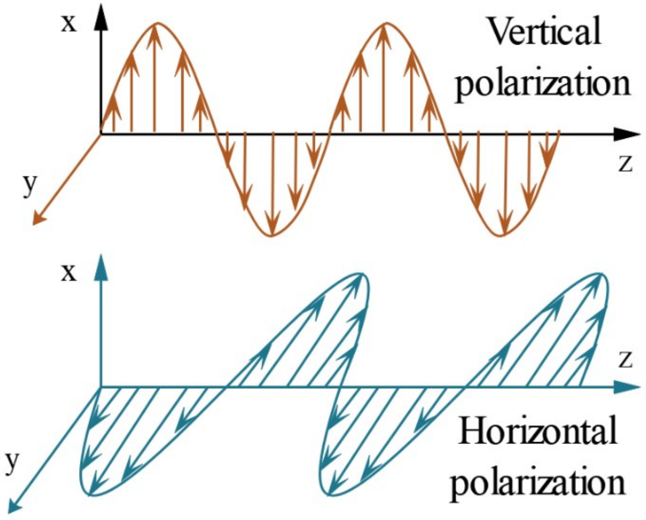


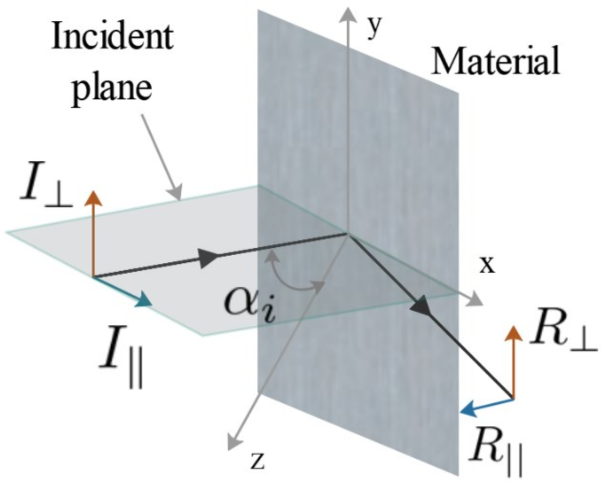


- ✓ elliptical polarization
- ✓ linear polarization
- ✓ Circular polarization

Basic Idea

Reflection of polarized electromagnetic waves





Fresnel reflection coefficients:

$$\Re_{hp} = \frac{\cos\alpha - \sqrt{\varepsilon - \sin^2\alpha}}{\cos\alpha + \sqrt{\varepsilon - \sin^2\alpha}}$$

$$\Re_{vp} = -\frac{\varepsilon\cos\alpha - \sqrt{\varepsilon - \sin^2\alpha}}{\varepsilon\cos\alpha + \sqrt{\varepsilon - \sin^2\alpha}}$$

$$\mathcal{P} = \frac{\Re_{vp}}{\Re_{hp}} = |\mathcal{P}|e^{j\Psi}$$

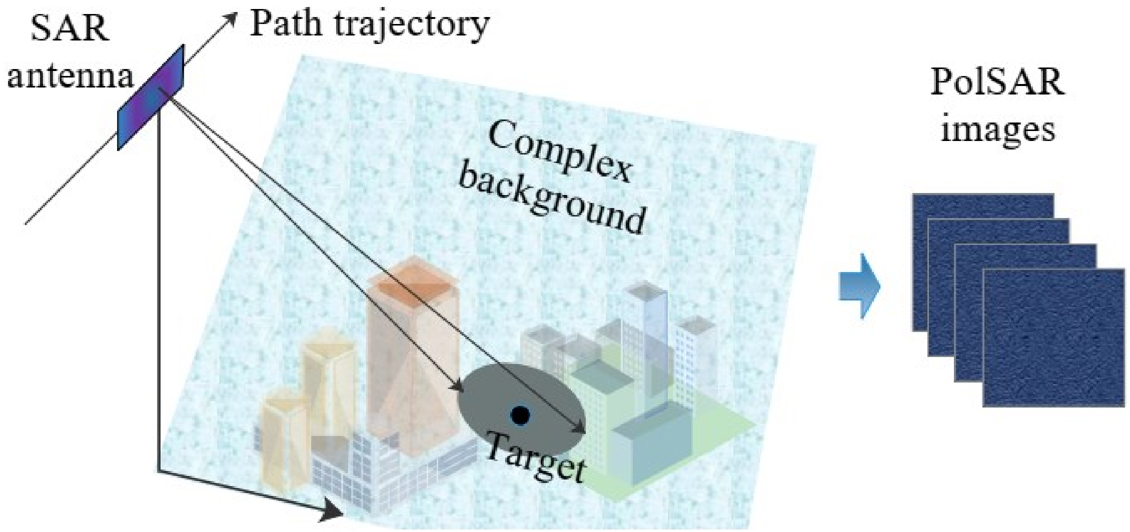
- ✓ The complex permittivity can uniquely identify the material
- ✓ The complex permittivity can be calculated from orthogonal polarizations

The complex permittivity:

$$\varepsilon = \left[1 + \frac{4\mathcal{P}}{(1-\mathcal{P})^2}\sin^2\alpha\right]\tan^2\alpha$$

Basic Idea

Polarimetric synthetic aperture radar (PolSAR) imaging



The normalized covariance matrix:

$$\langle \mathbf{C} \rangle = \langle \mathbf{k}\mathbf{k}^{\dagger} \rangle$$

$$\mathbf{k} = \frac{1}{\sqrt{2}} [S_{\mathrm{HH}} + S_{\mathrm{VV}}, S_{\mathrm{HH}} - S_{\mathrm{VV}}, 2S_{\mathrm{HV}}]^T$$

- ✓ Subdivide the reflected surface into many small reflected areas like PolSAR
- ✓ Measure the complex permittivity of each reflected area and distinguish the edges

Challenge 1 – Inaccurate of Phase Values

The complex permittivity: $\varepsilon = \left[\mathbf{1} + \frac{\mathbf{4}\mathcal{P}}{(\mathbf{1}-\mathcal{P})^{\mathbf{2}}} \sin^{\mathbf{2}} \alpha\right] \tan^{\mathbf{2}} \alpha$

Power ratio → $|\mathcal{P}|$

Phase difference → Ψ

$$\operatorname{Re} \varepsilon = \left[1 + 4|\mathcal{P}| \frac{\left(1+|\mathcal{P}|^2\right) \cos \Psi - 2|\mathcal{P}|}{(1-2|\mathcal{P}| \cos \Psi + |\mathcal{P}|^2)^2} \sin^2 \alpha\right] \tan^2 \alpha$$

$$\operatorname{Im} \varepsilon = 4|\mathcal{P}| \frac{\left(1-|\mathcal{P}|^2\right) \sin \Psi}{(1-2|\mathcal{P}| \cos \Psi + |\mathcal{P}|^2)^2} \sin^2 \alpha \tan^2 \alpha$$

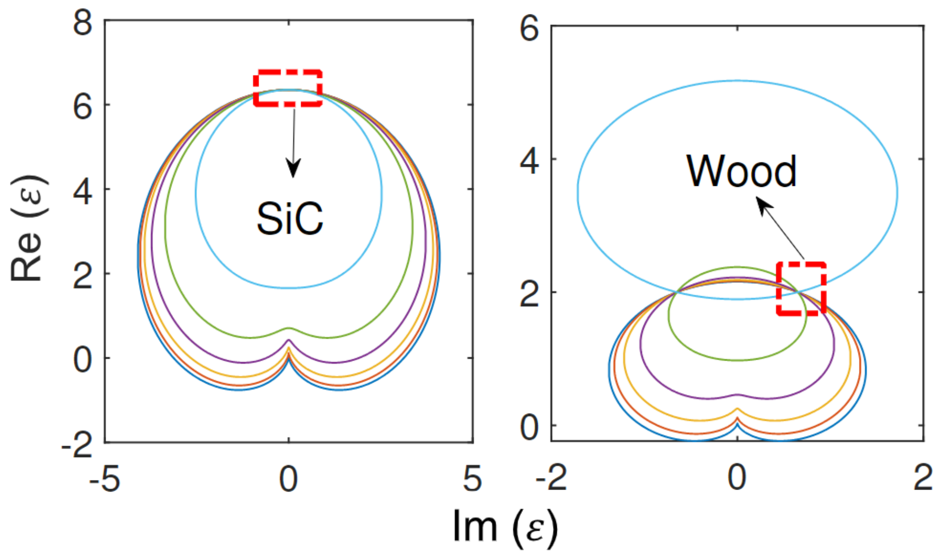
Unknown phase errors:

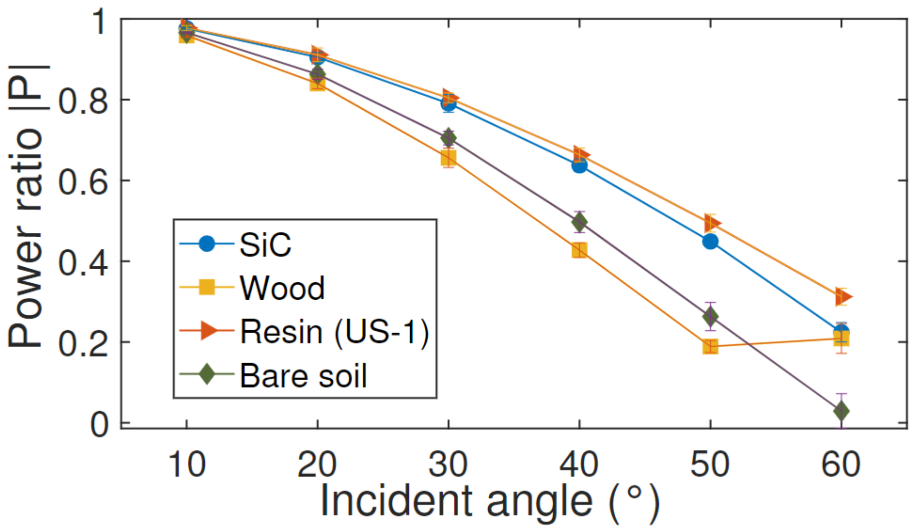
- ✓ Sample Frequency Offset
- ✓ Time of Flight
- ✓ Multipath

How to fine-grained estimate the complex permittivity of material when WiFi signal phase measurement is inaccurate?

Challenge 1 – Inaccurate of Phase Values

Our Solution: Multiple incident angles model





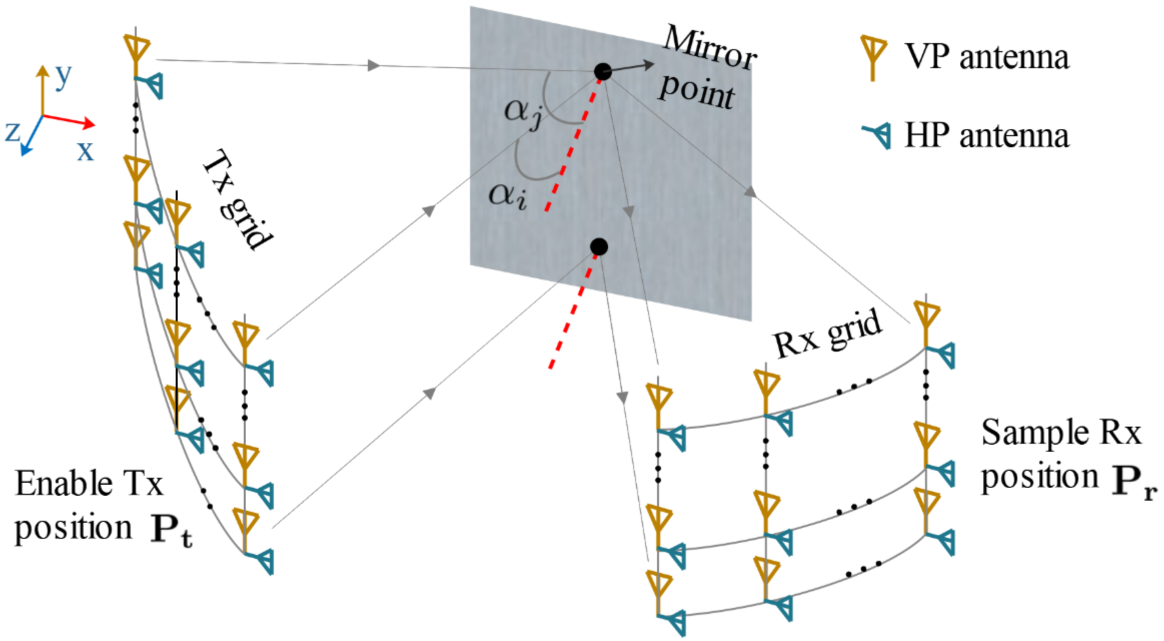
✓ Using the power ratio of the reflected orthogonally polarized signals at different incident angles, the complex permittivity of the material can be approximated

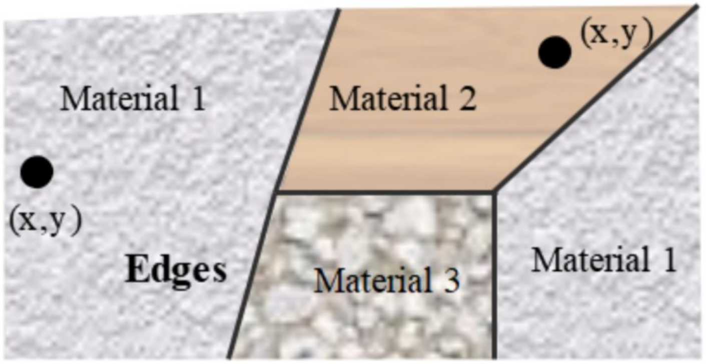
✓ The power ratios of orthogonally polarized signals reflected by different materials are different at some incident angles

$$\mathbf{g} = \left[|\mathcal{P}^1|, |\mathcal{P}^2|, \cdots, |\mathcal{P}^M|\right]$$

Challenge 1 – Inaccurate of Phase Values

Our Solution: Multiple incident angles model





- ✓ We construct the Tx antenna grid and the Rx antenna grid around the target material, and when Tx and Rx are at certain position (P_t^k, P_r^k), the condition of certain incident angle α^k to certain mirror point k can be formed
- ✓ Scan each mirror point on 2D and identify the material type

Challenge 2 – Fine-grained Parameters

Multipath decomposition: $\mathbf{H} = \sum_{\mathbf{l}=1}^{\mathbf{L}} \mathbf{H}\left(\varphi_{\mathbf{l}}, \mathbf{\Phi}_{\mathbf{l}}, \gamma_{\mathbf{l}}, \tau_{\mathbf{l}}\right) + \mathbf{W}$

AoD, AoA, delay

Multidimensional estimator

$$(\hat{\varphi}, \hat{\Phi}, \hat{\tau}) = \underset{\varphi, \Phi, \gamma, \tau}{\arg\max} |z(\varphi, \Phi, \tau)|$$

Attenuation

$$\hat{\gamma} = \frac{z(\hat{\varphi}, \hat{\Phi}, \hat{\tau})}{N_{ant} \cdot T_s}$$

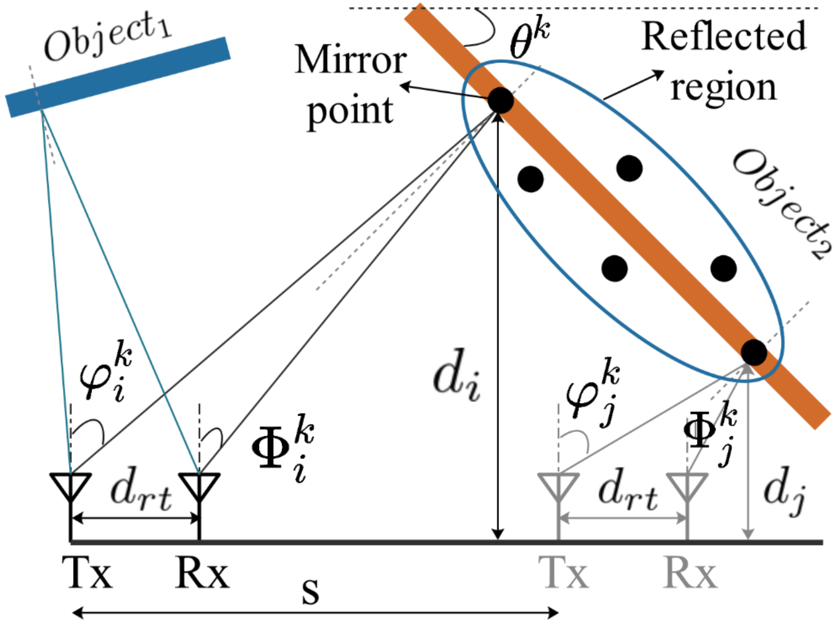
Parameters to be solved:

- ✓ Position (x^k, y^k, z^k) and orientation θ^k of reflected mirror point
- ✓ Incident angle α^k and reflected power ratio $|P^k|$

How to use COTS WiFi to mark reflected areas with centimeter-level accuracy and extract reflected power ratio?

Challenge 2 – Reflected Power Extraction

Our Solution: Equal-complementary angle model



$$\hat{\varphi}_i + \hat{\Phi}_i = \hat{\varphi}_{i+1} + \hat{\Phi}_{i+1}, i = 1, 2, \cdots$$

$$(\hat{\varphi'}^k, \hat{\Phi'}^k) = \frac{1}{N^k} \sum_{i=1}^{N^k} \underset{\hat{\varphi}^k, \hat{\Phi}^k}{\arg\min} ||(\hat{\varphi}_i^k + \hat{\Phi}_i^k) - (\hat{\varphi}_j^k + \hat{\Phi}_j^k)||^2$$

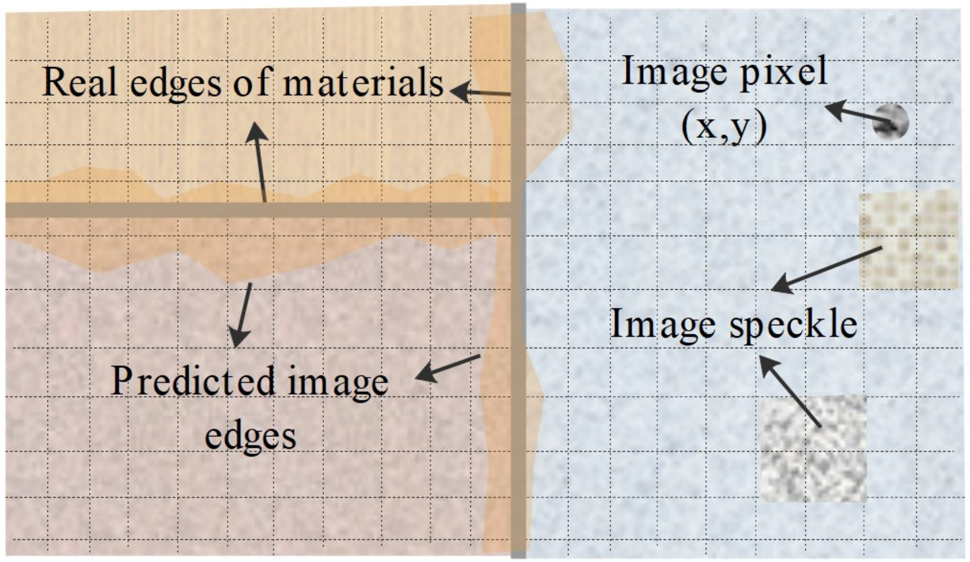
$$\hat{\tau'}^k = \frac{\hat{d}^k \ (\sec \hat{\varphi'}^k + \sec \hat{\Phi'}^k)}{c} = \frac{d_{rt}^k \ (\sec \hat{\varphi'}^k + \sec \hat{\Phi'}^k)}{(\tan \hat{\varphi'}^k - \tan \hat{\Phi'}^k) \cdot c}$$

$$\hat{\theta}^k = \frac{\hat{\varphi}^k + \hat{\Phi}^k}{2} + \arctan \frac{z_r^k - z_t^k}{x_r^k - x_t^k}$$

$$\hat{\alpha}^k = \frac{\hat{\varphi}^k - \hat{\Phi}^k}{2} \qquad |\hat{\mathcal{P}}^k| = \frac{|\hat{\gamma}_{vp}^k|^2}{|\hat{\gamma}_{hp}^k|^2}$$

Challenge 3 – Material Edges Refinement

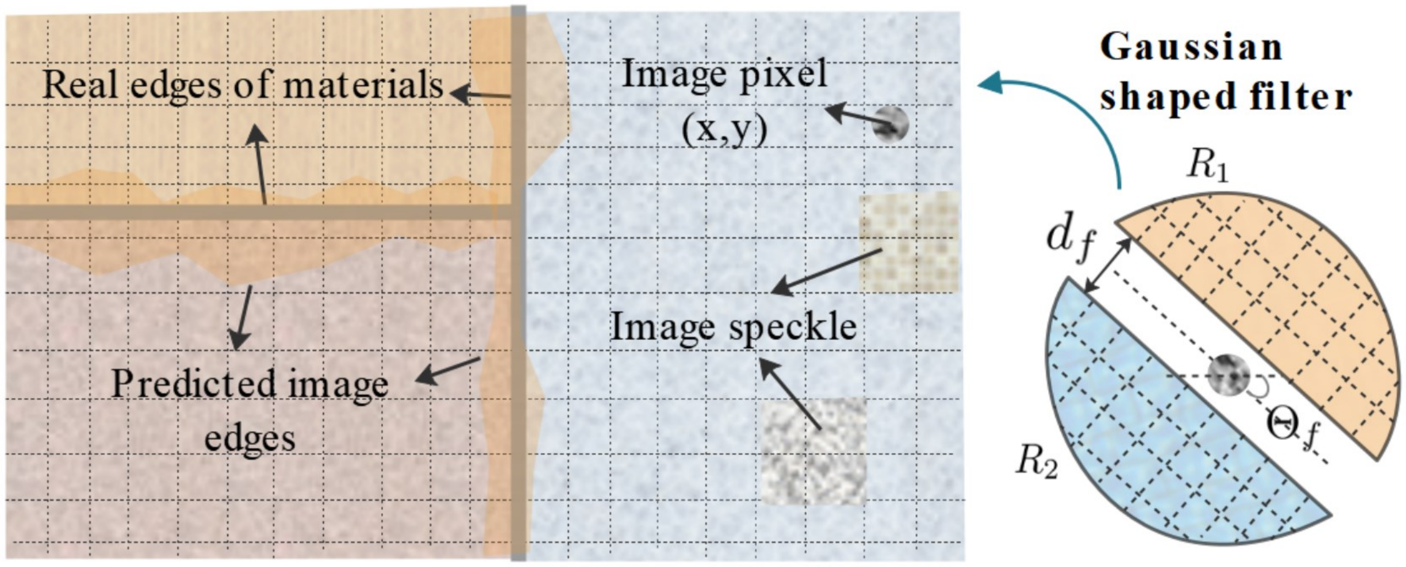
Problem: Strong speckle



How to remove the influences of strong speckle and refine material edges?

Challenge 3 – Material Edges Refinement

Our Solution: Gaussian shaped filter and curve fitting



Define:

Material type

$$C(x,y) = \begin{cases} 0, & T(x,y) = T_1 = T_2 \\ 1, & T(x,y) \neq T_1 \neq T_2, \\ 2, & T(x,y) = T_1 \neq T_2. \end{cases}$$

Gaussian kernel

$$\mathbf{Z} = \frac{\sum_{(x,y)} W(x,y) C(x,y)}{\sum_{(x,y)} W(x,y)}$$

$$D(\mathbf{Z}_1, \mathbf{Z}_2) = ||\mathbf{Z}_1|| + ||\mathbf{Z}_2||$$

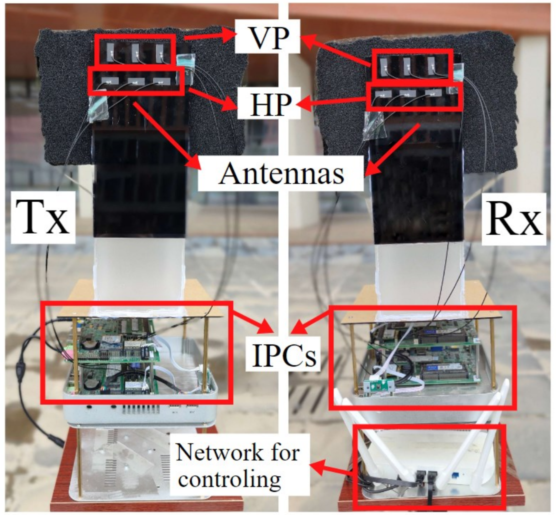
$$D_{max} = \max \ D(\mathbf{Z}_1, \mathbf{Z}_2, \Theta)$$

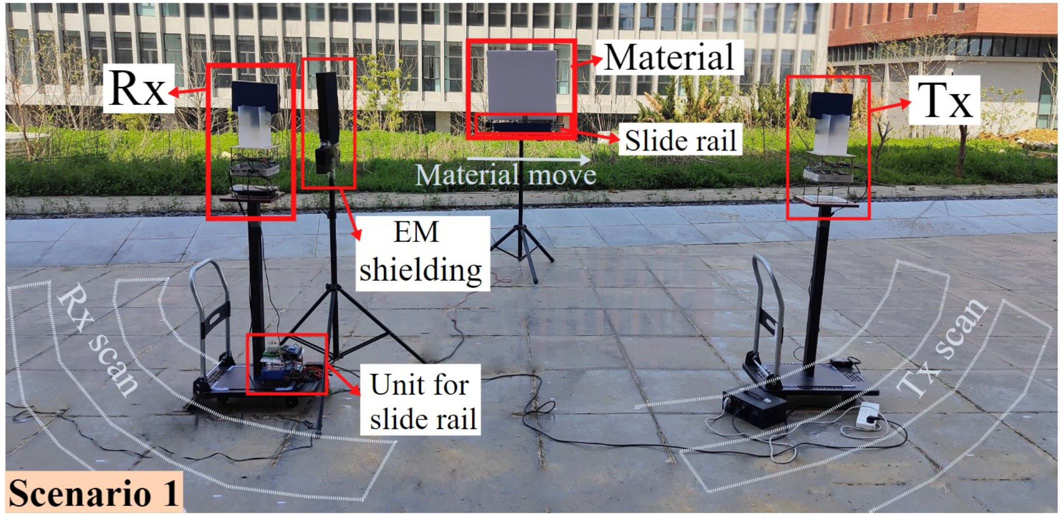
$$\Theta_{max} = \arg\max_{\Theta} D(\mathbf{Z}_1, \mathbf{Z}_2, \Theta)$$

If $D_{max} > D_{threshold}$: edge pixel

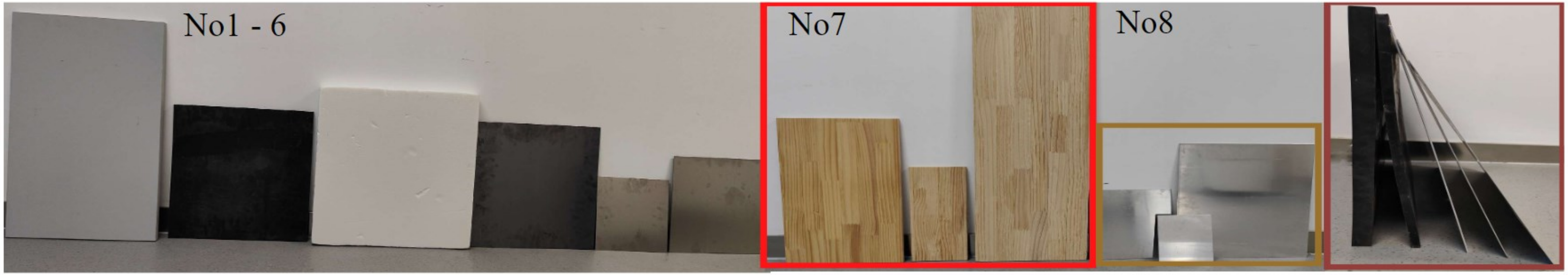
Evaluation Setup

Hardware and Scenarios

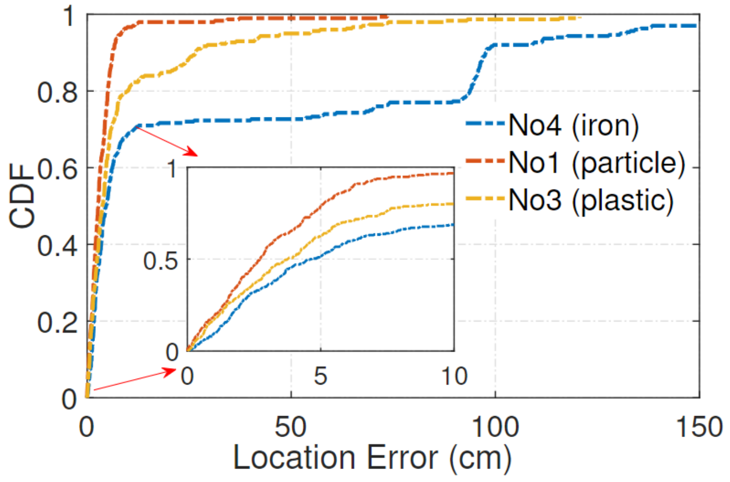


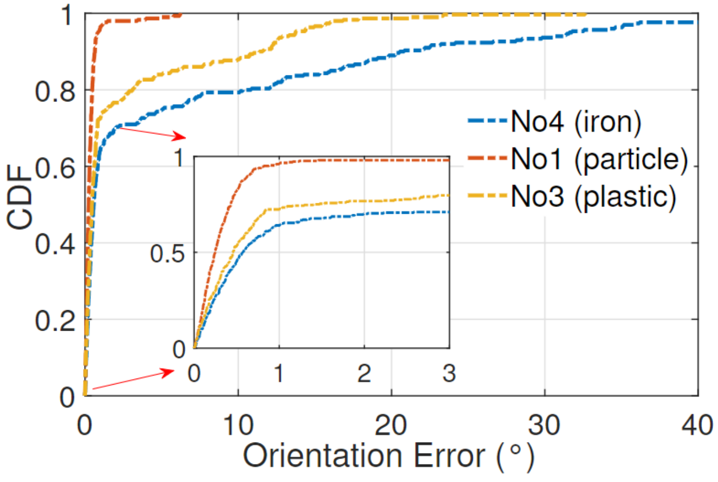


Materials

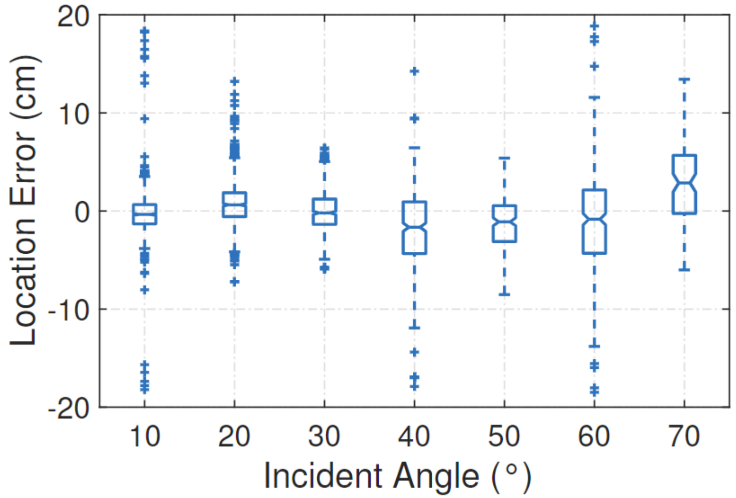


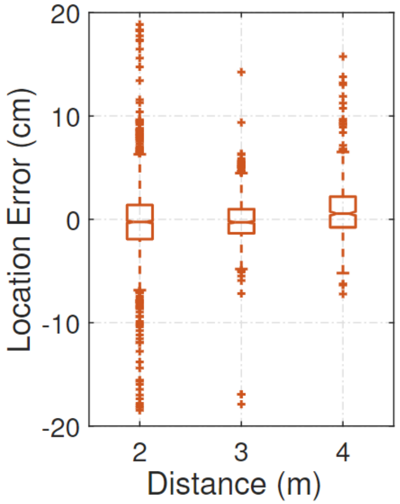
Accuracy of Object Location and Orientation





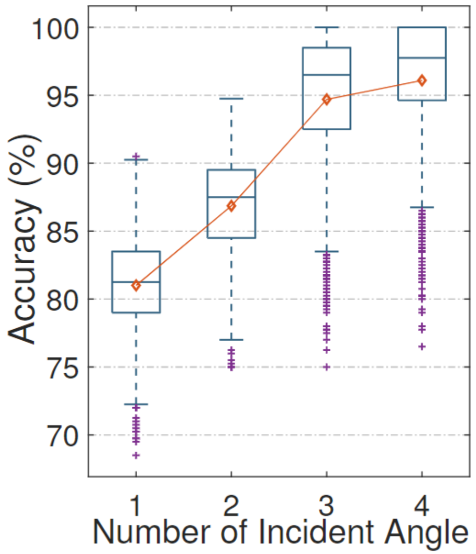
- ✓ **Median location error： 3cm**
- ✓ **Median orientation error： 1°**



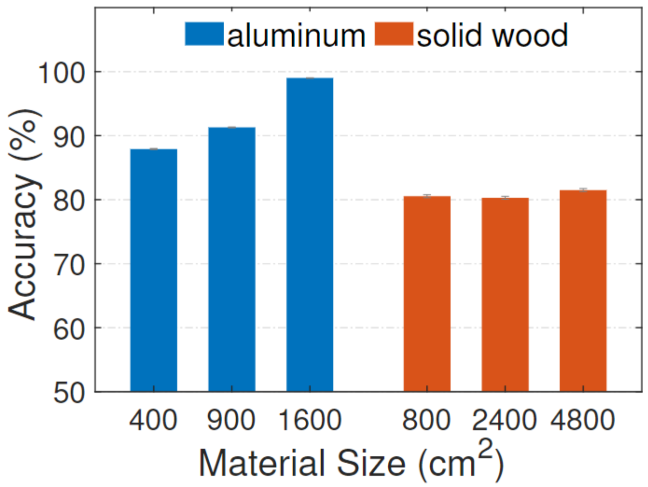


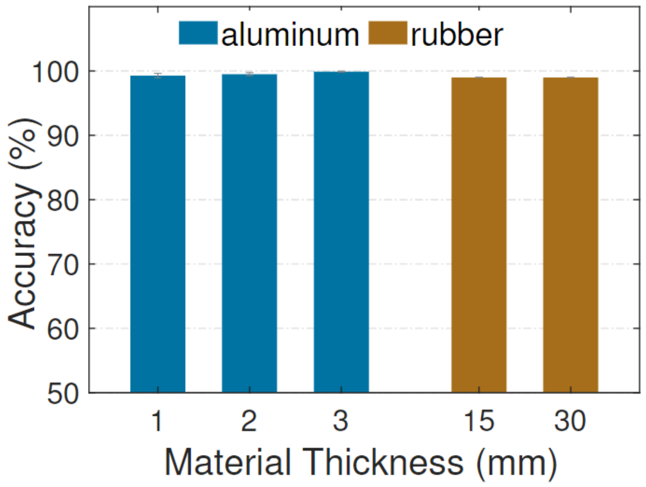
- ✓ **Robsut to different incident angles**
- ✓ **Robust to different distances**

Accuracy of Identifying Various Materials



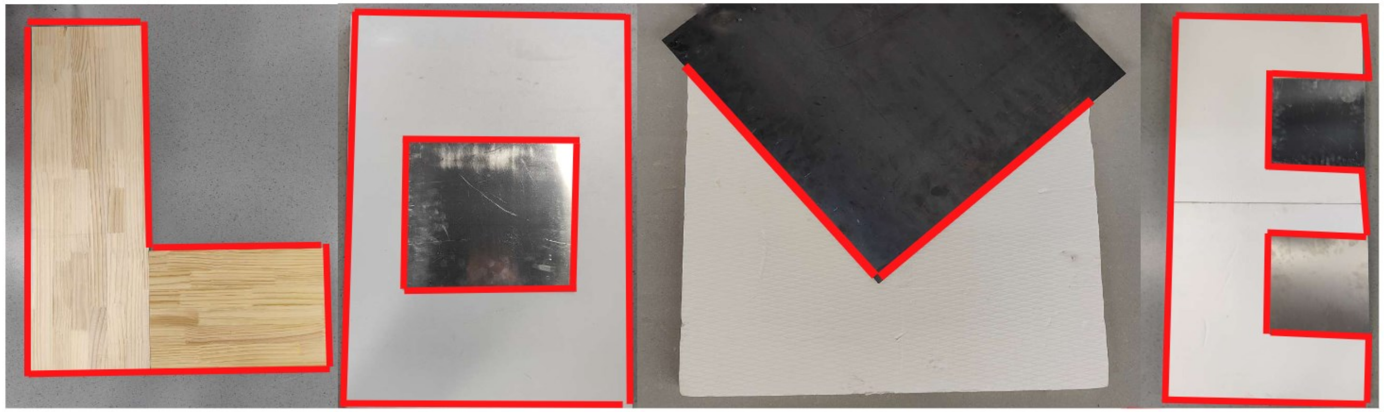
- ✓ Material identification accuracy: 96%
- ✓ Robust to different number of incident angles

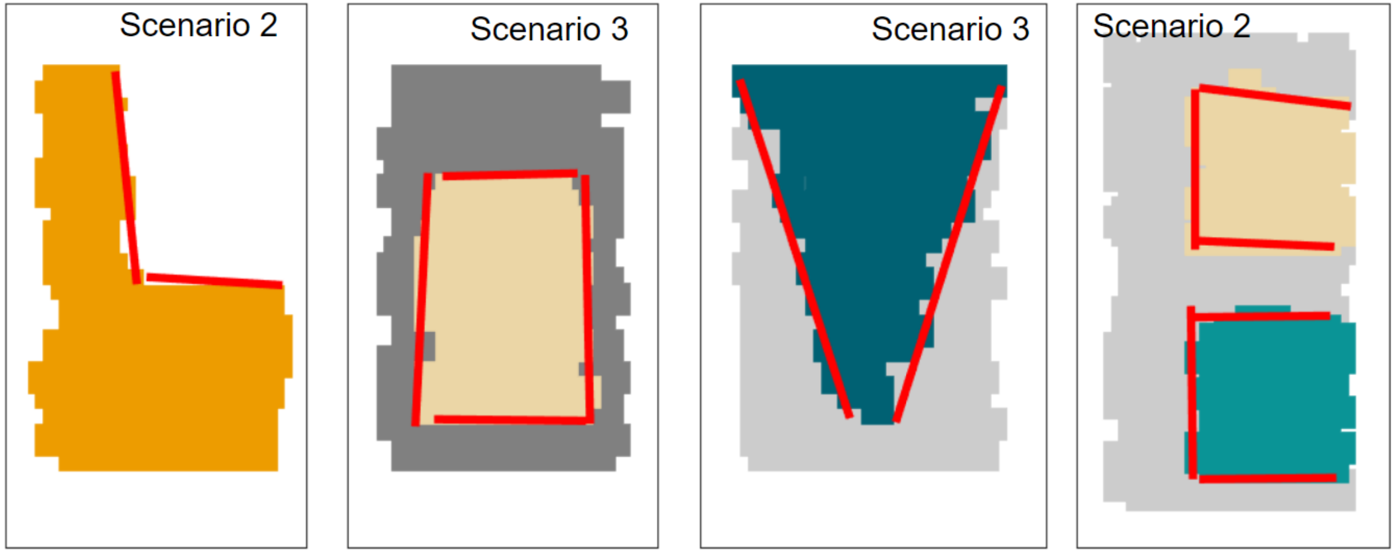




- ✓ Robust to different sizes of material
- ✓ Robust to different thicknesses of material

Accuracy of Detecting Multiple Material Edges





- ✓ Fine-grained edges detection

Conclusion

- ✓ We design Wi-Painter, a model-driven attempt to perform fine-grained detection of materials and edges using COTS WiFi devices.
- ✓ We build a multi-incident angle model that can accurately estimate various materials using only the power ratio.
- ✓ We form a two-dimensional image simultaneously on the basis of identifying the material type of each pixel.
- ✓ Our real-world evaluations show that Wi-Painter performs well across different material types, sizes, thicknesses, and environments.

Thank you!