SMART: Screen-based Gesture Recognition on Commodity Mobile Devices

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MobiCom 2021

In-air gesture control is natural and contactless

Gesture control via hardware on mobile devices

Image

[CVPR’13,UIST’14]

Acoustic

[CHI’12,MobiCom’16]

Wi-Fi

[Mobicom’15,Ubicomp’16]

Privacy concerns

Background noise

Gesture control via hardware modification

Huawei
Mate40

depth camera

Google
Pixel 4

mmWave radar

Can we support in-air gesture recognition on legacy devices ***without hardware modification****?*

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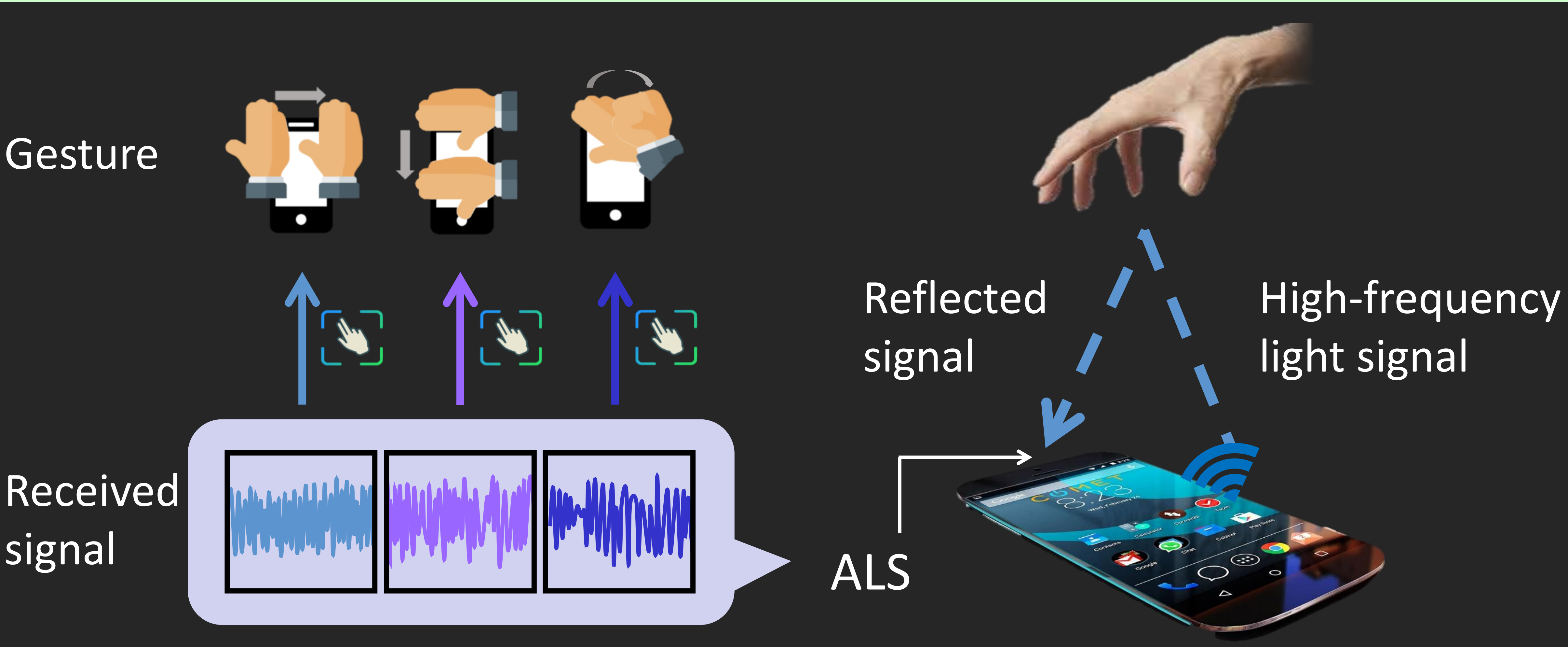

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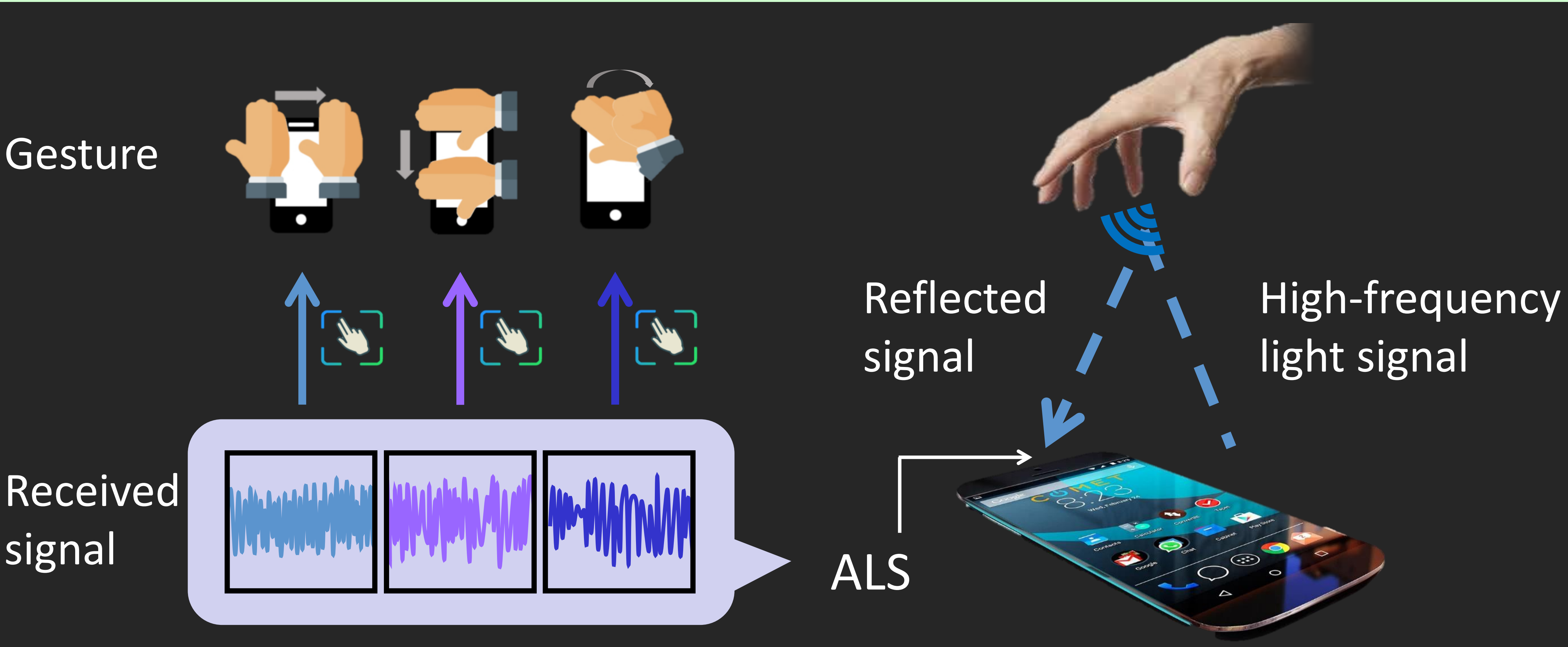

Gesture

Received signal

Reflected signal

High-frequency light signal

ALS

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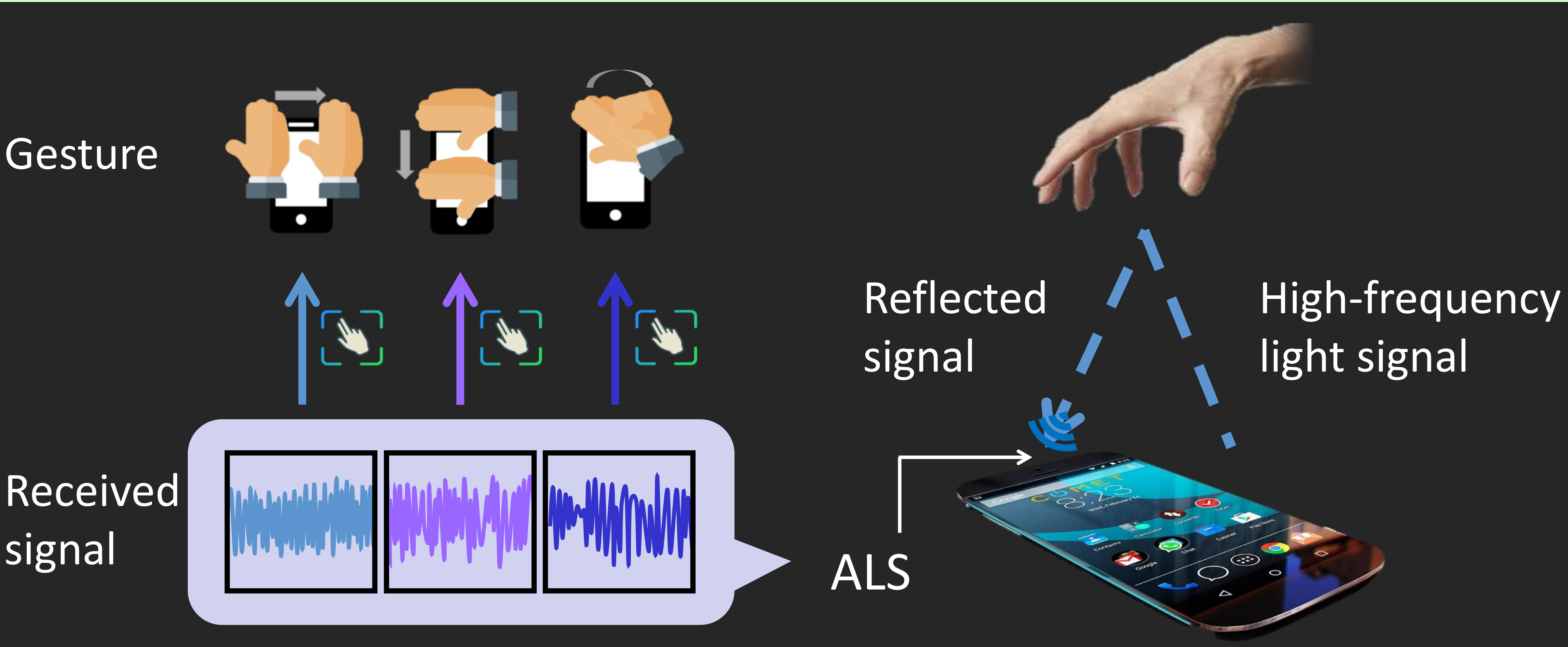
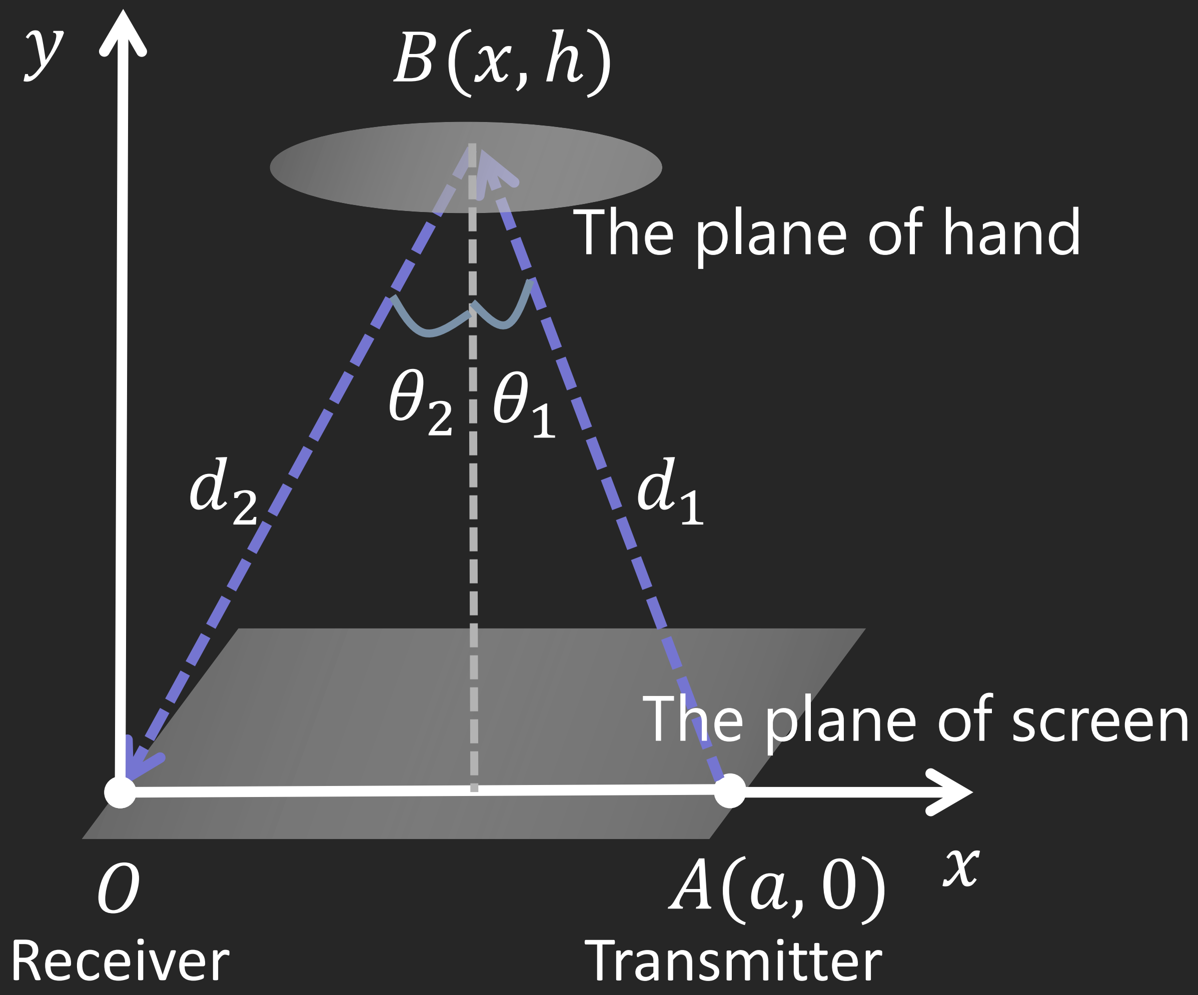


What is the relationship between the received light power and the hand gesture?

Model the “Screen-Hand-ALS” channel



Calculate received power

$$I_O = \boxed{I_A} \cdot \boxed{l_{AB}} \cdot \boxed{l_B} \cdot \boxed{l_{BO}} \cdot \boxed{l_O}$$

Lambert radiation

$$= I_A \cdot c \cdot \frac{\cos\theta_1}{{d_1}^2} \cdot \frac{\cos{\theta_2}^2}{{d_2}^2}$$

$$= I_A \cdot c \cdot \frac{h^3}{\left((x-a)^2+h^2\right)^{\frac{3}{2}}\left(x^2+h^2\right)^2}$$

I_O: signal power received by point O.

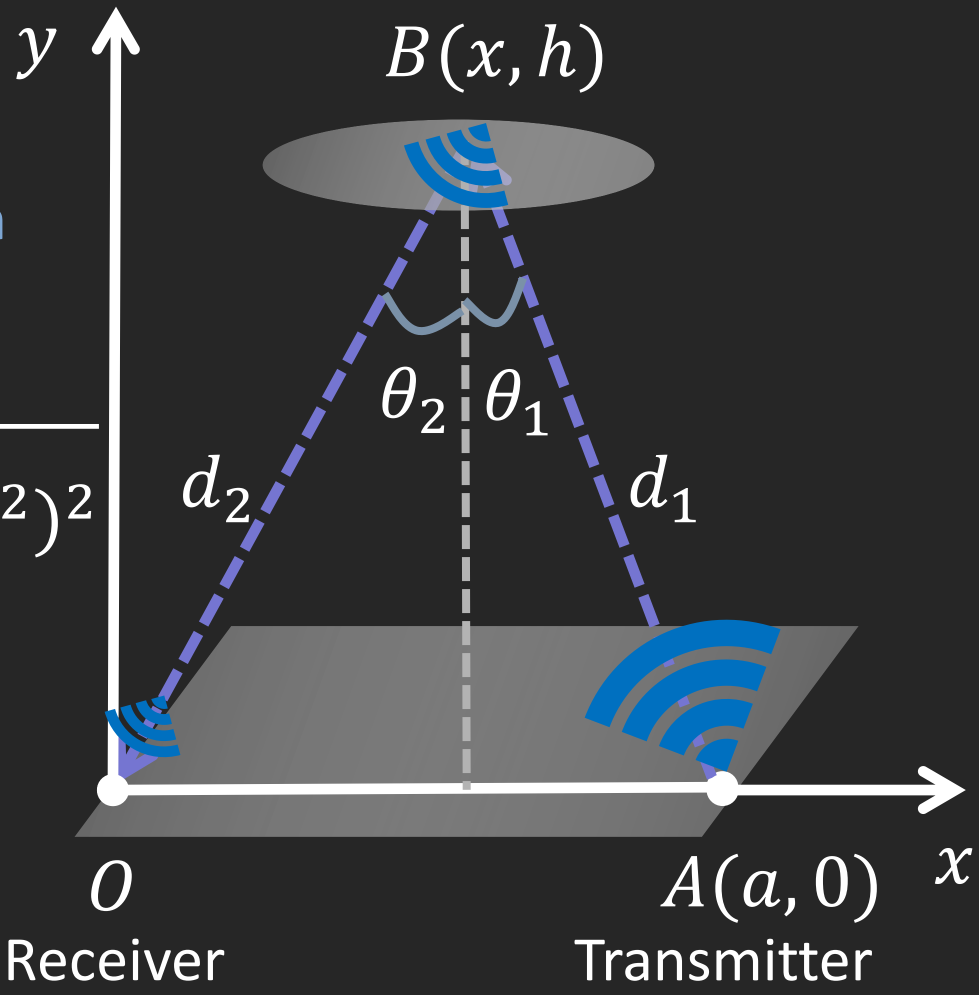
I_A: signal power transmitted by point A.

l_{AB}: loss from A to B.

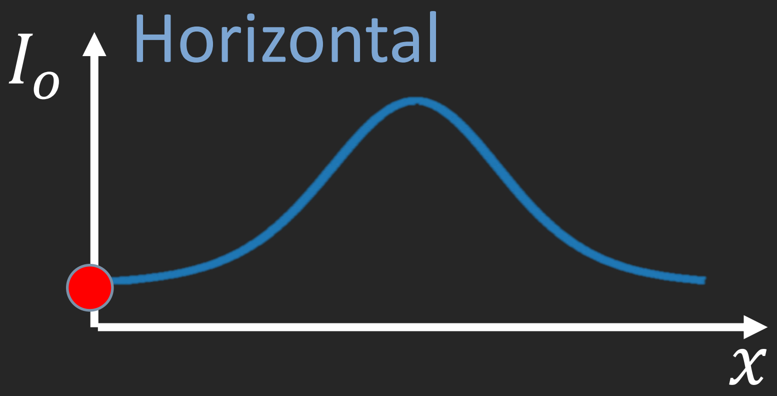
l_{BO}: loss from B to O.

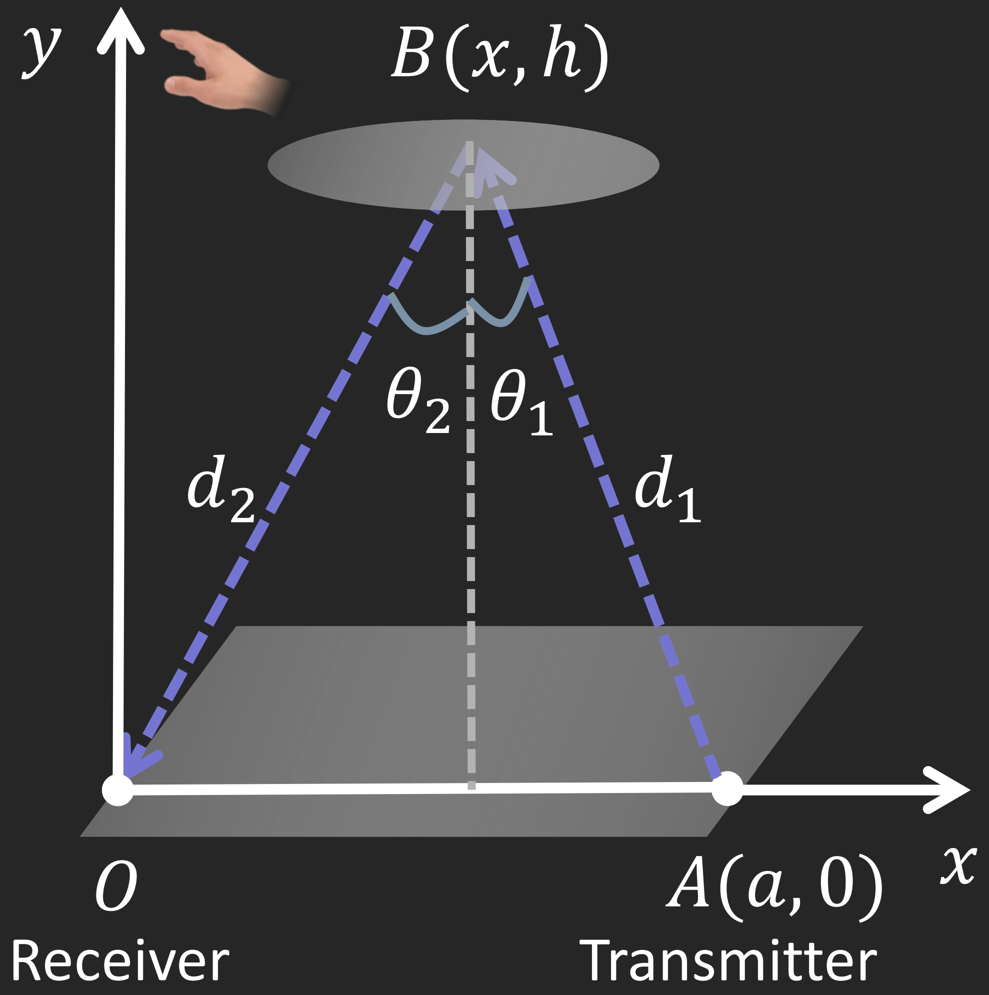
l_B: loss at point B.

l_O: loss at point O.



Hand movement and received power





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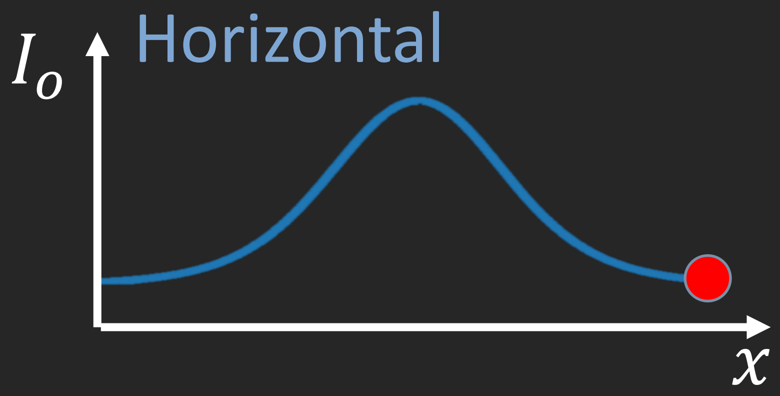

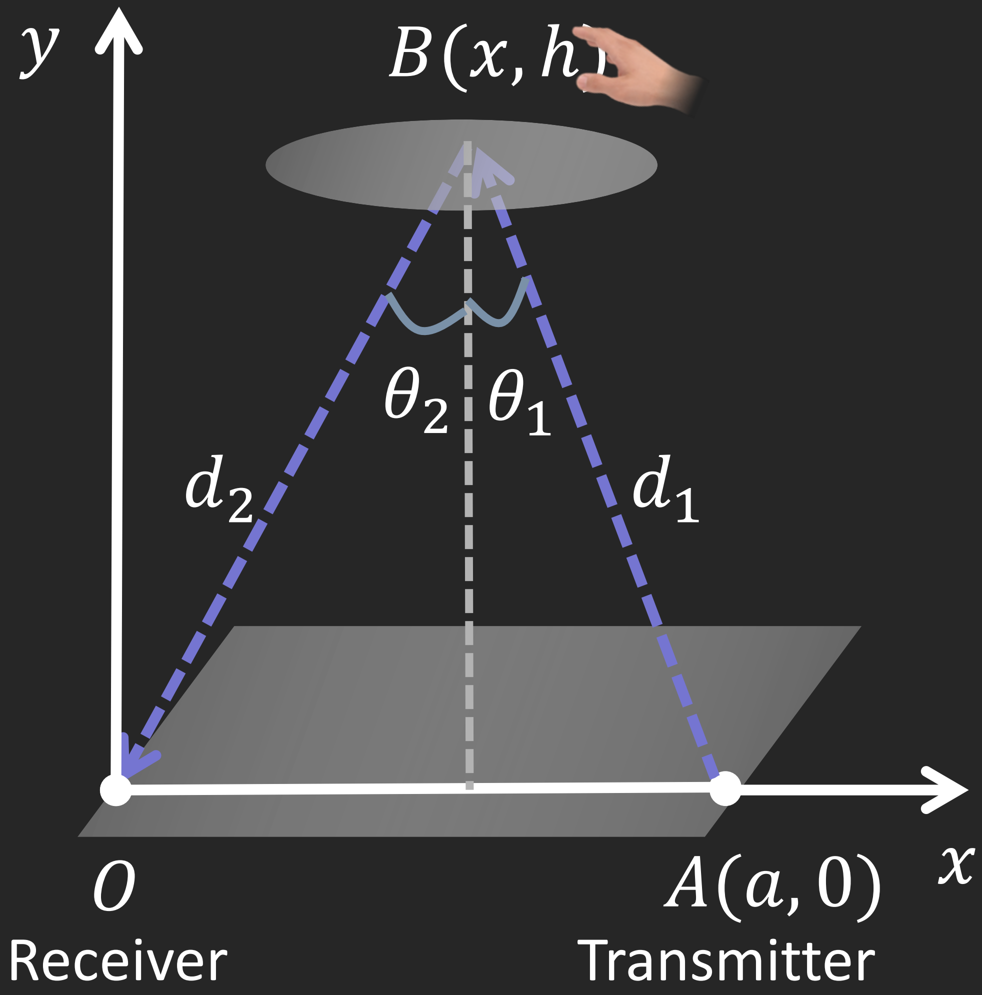

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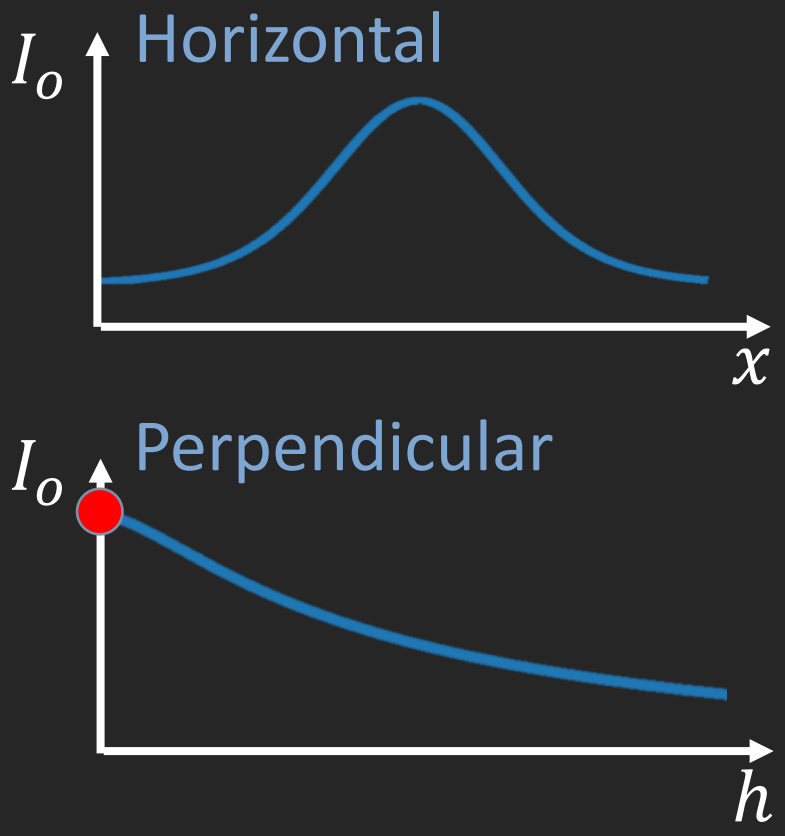

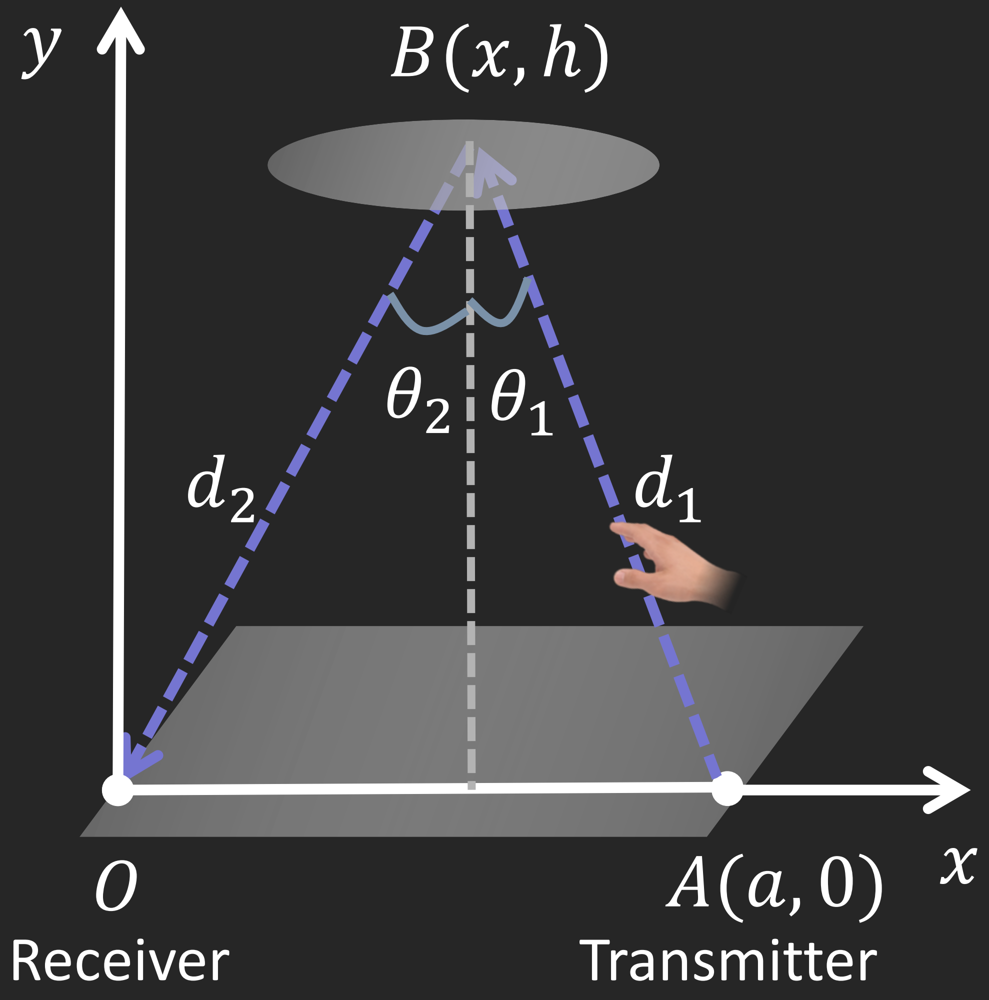

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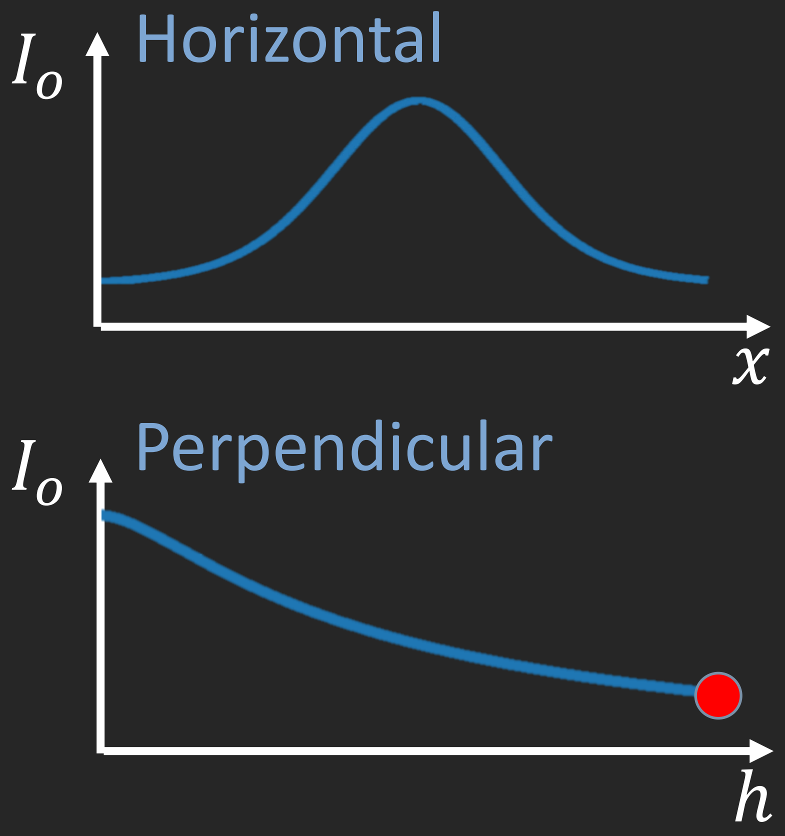
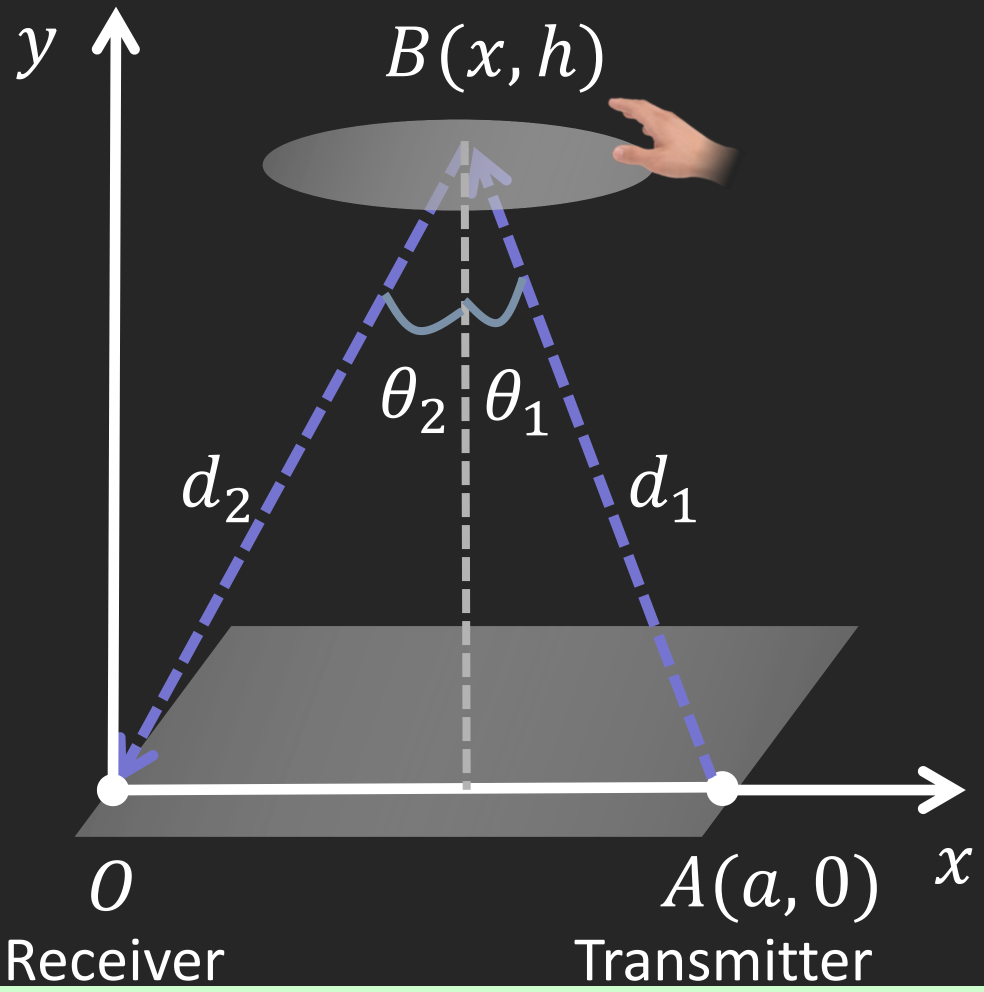




The fundamental working principle of SMART

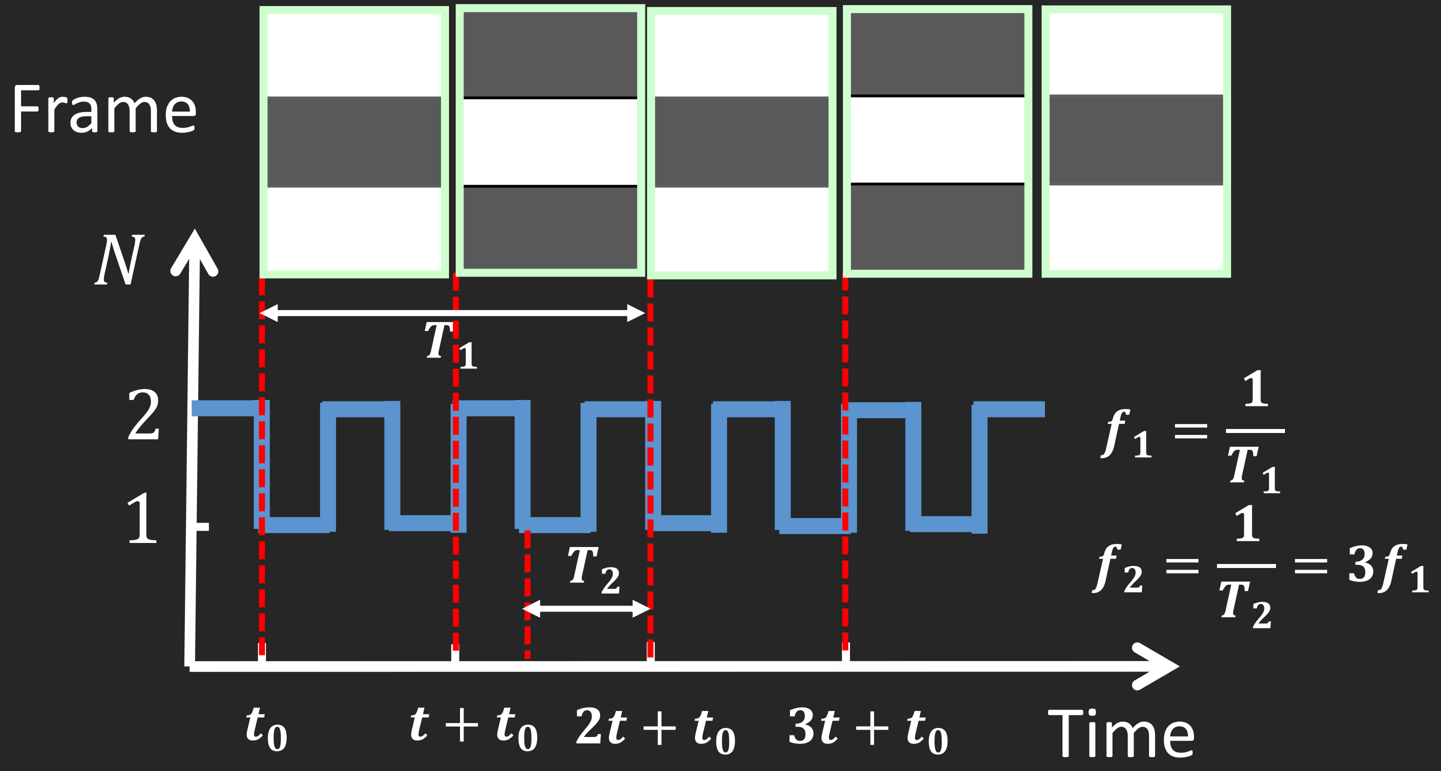
Screen’s refresh rate limits modulated frequency

Refresh time per frame	$\boldsymbol{t}(=\frac{\mathbf{1}}{f_r})$	$\mathbf{2}\boldsymbol{t}$	$\mathbf{3}\boldsymbol{t}$	**… …**	$\mathbf{n}\boldsymbol{t}$
Frequency	f_1	$\frac{f_1}{2}$	$\frac{f_1}{3}$	**… …**	$\frac{f_1}{n}$

Lower frequency

Higher frequency light signals are needed since human eyes are sensitive to low frequency flickering

Transmit high frequency signal



$$f_1 = \frac{1}{T_1}$$

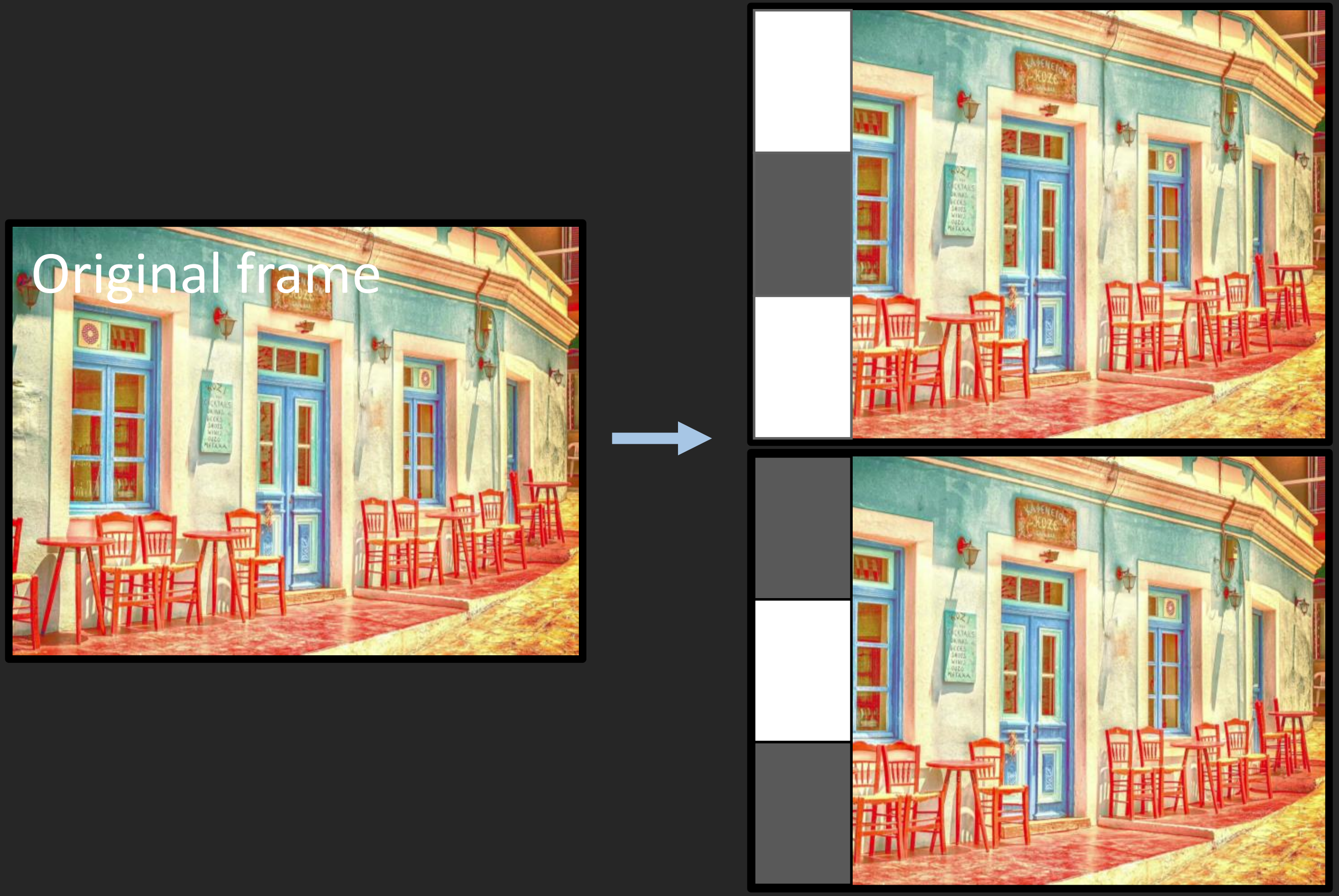
$$f_2 = \frac{1}{T_2} = 3f_1$$

N: the number of bright blocks

t: refreshing time per frame

Hide signals in the screen content

Color decomposition of each pixel



Color space: RGB -> CIE 1931

$$\max \Delta Y = |Y_1 - Y_2|$$

$$s.t. \quad x_1 = x_2 = x_0,$$

$$y_1 = y_2 = y_0,$$

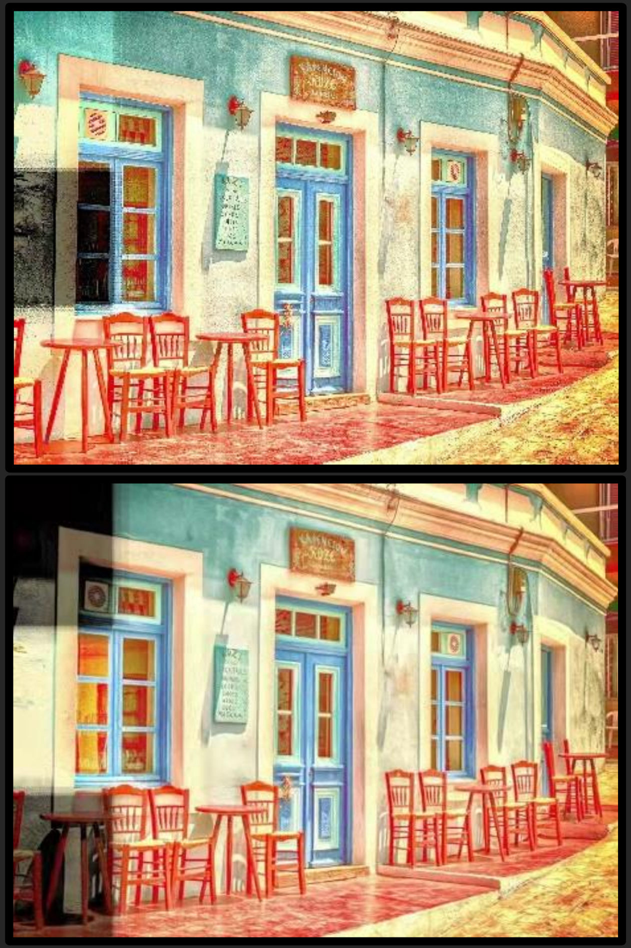
$$Y_0 = \frac{Y_1 + Y_2}{2}$$

Maximum luminance change.

The same chromaticity.

Color addictive rule.

Color decomposition of each pixel



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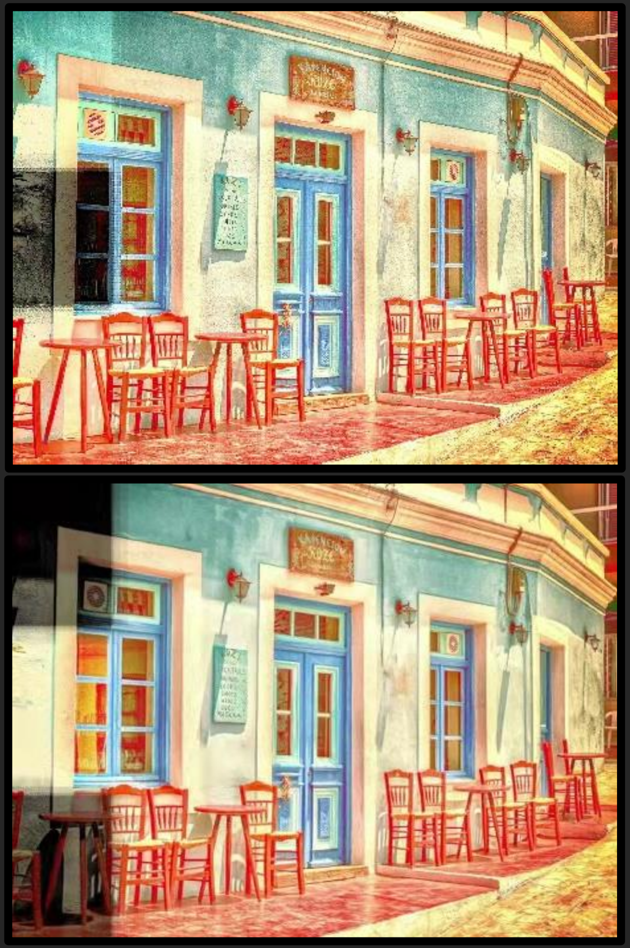

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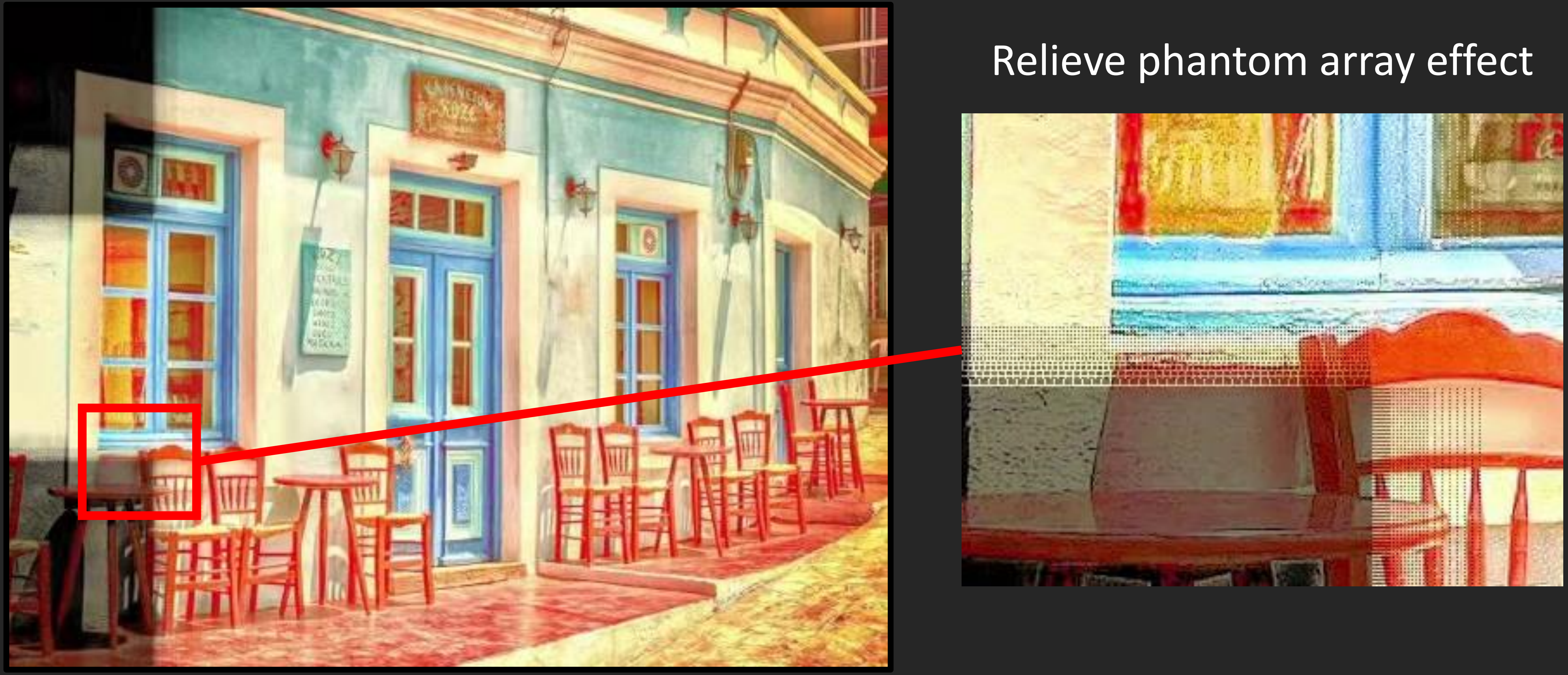
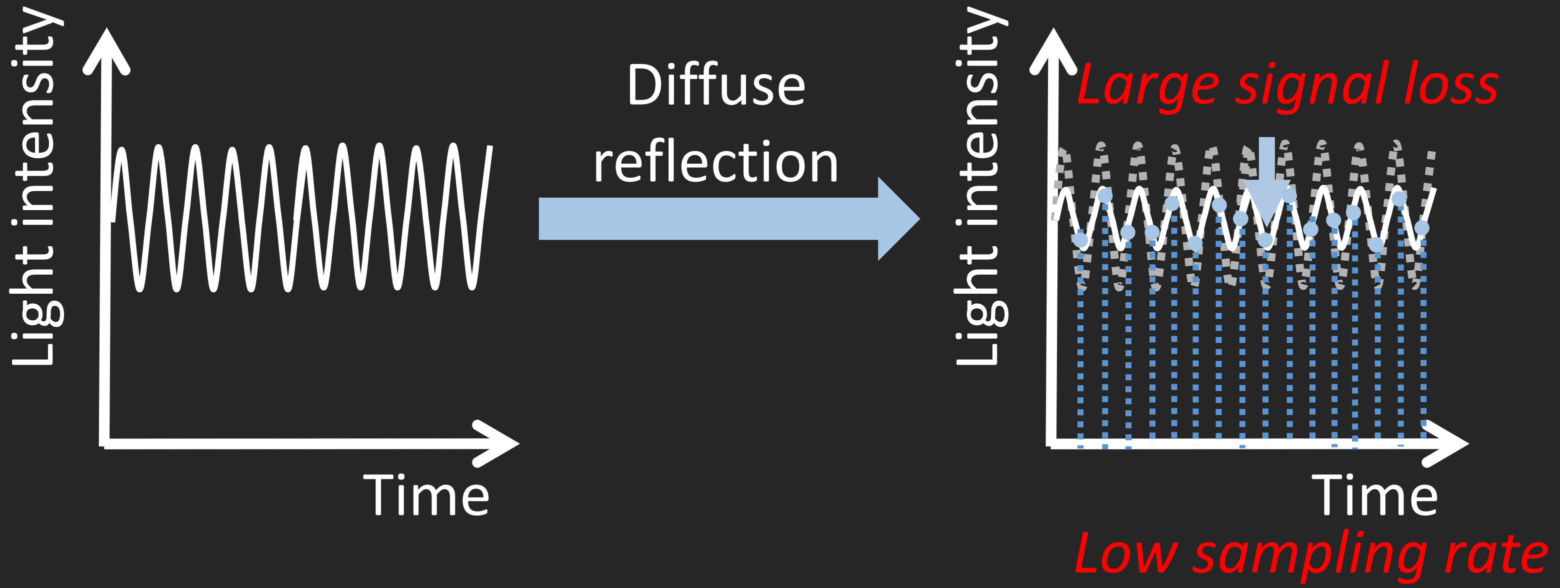
Edge smoothing



Relieve phantom array effect

Signal received by ALS is low-quality



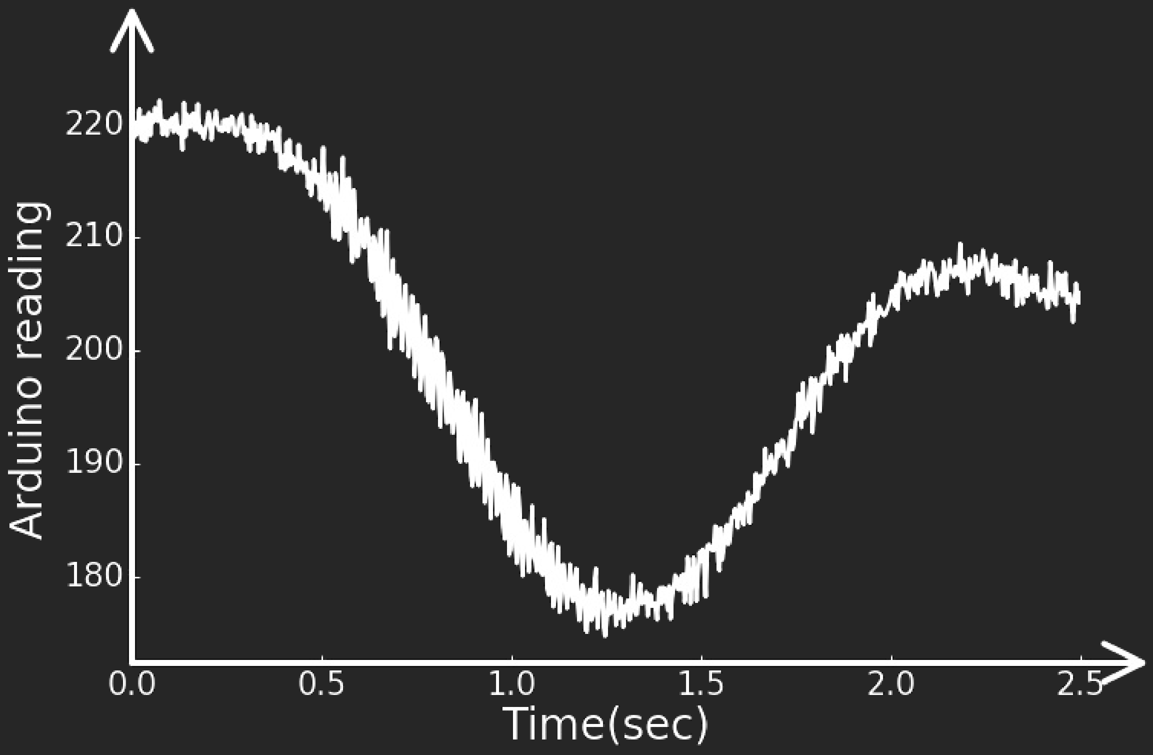
Diffuse reflection

Large signal loss

Low sampling rate

Segmentation according to reflected power

Raw signal



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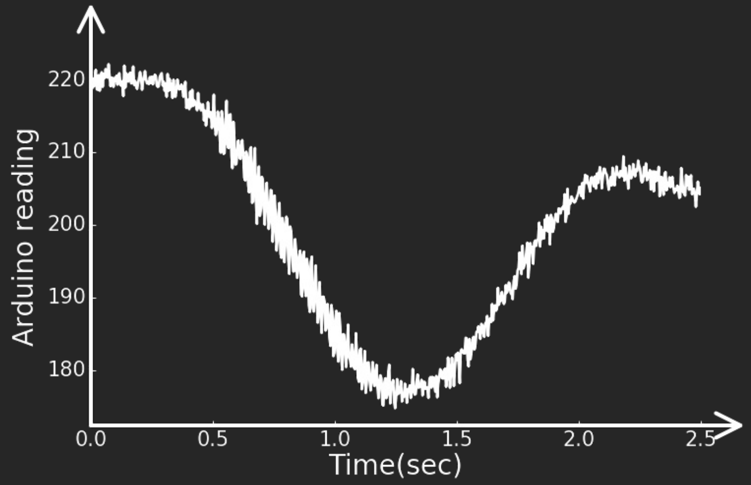
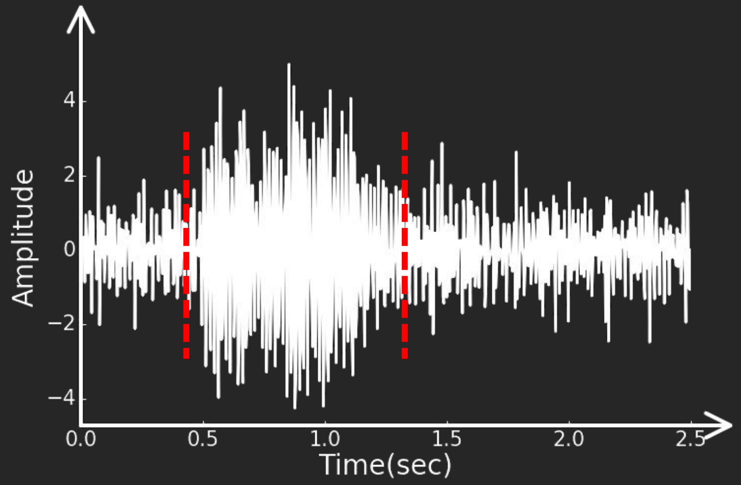


High-pass filter

Reflected signal



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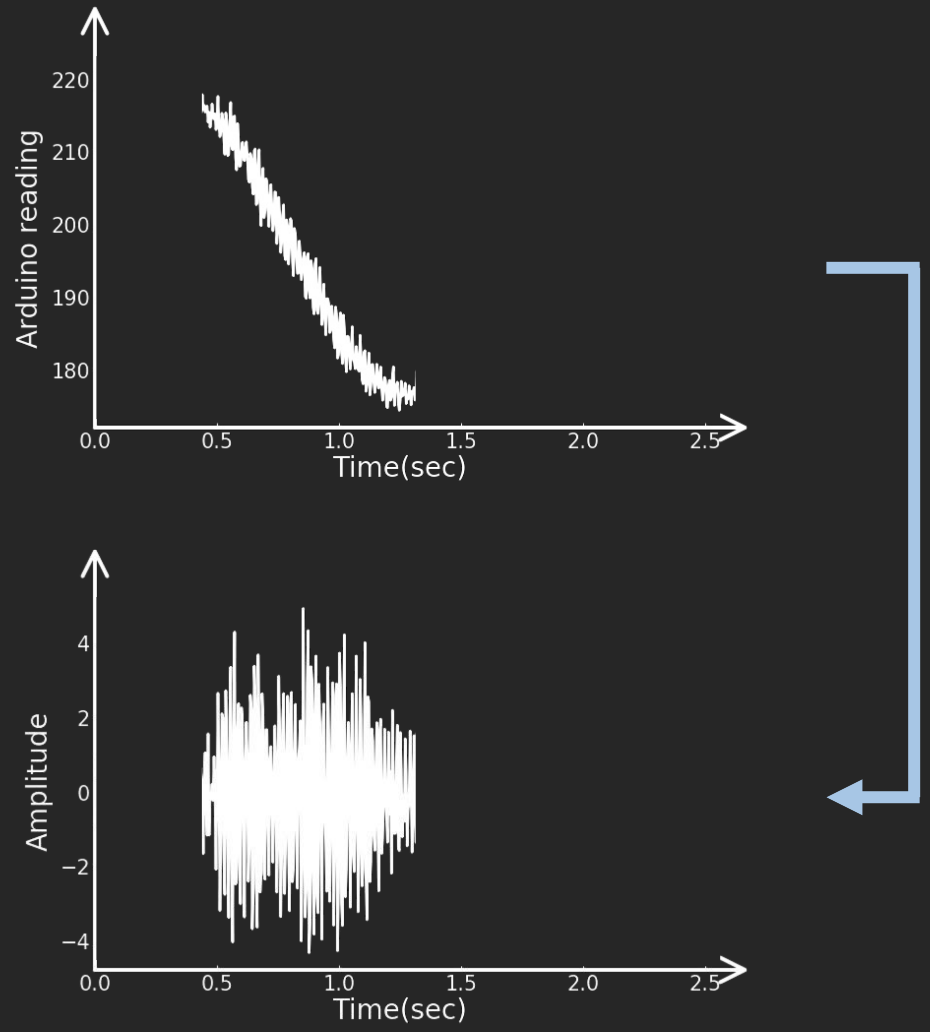
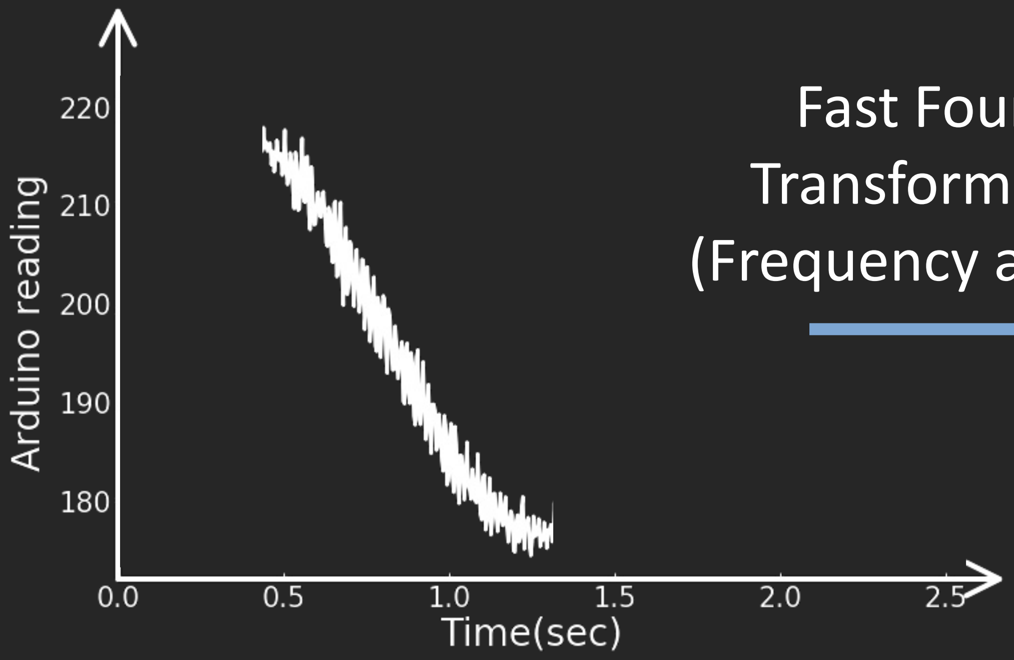


Raw signal

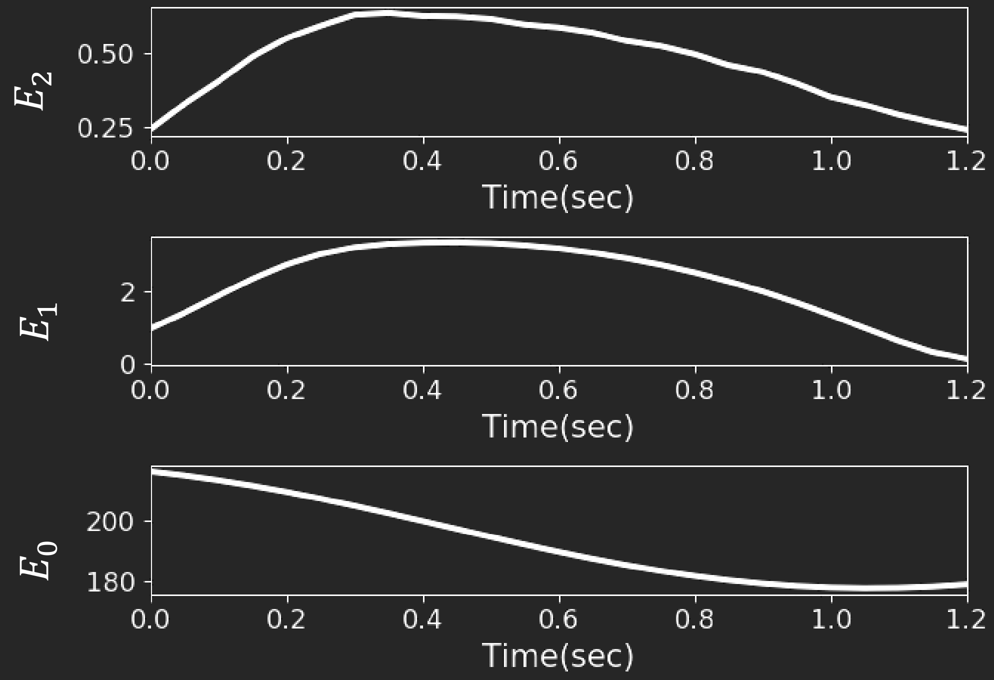
High-pass filter

Reflected signal

Signal pre-processing and classification



Fast Fourier Transformation (Frequency aliasing)



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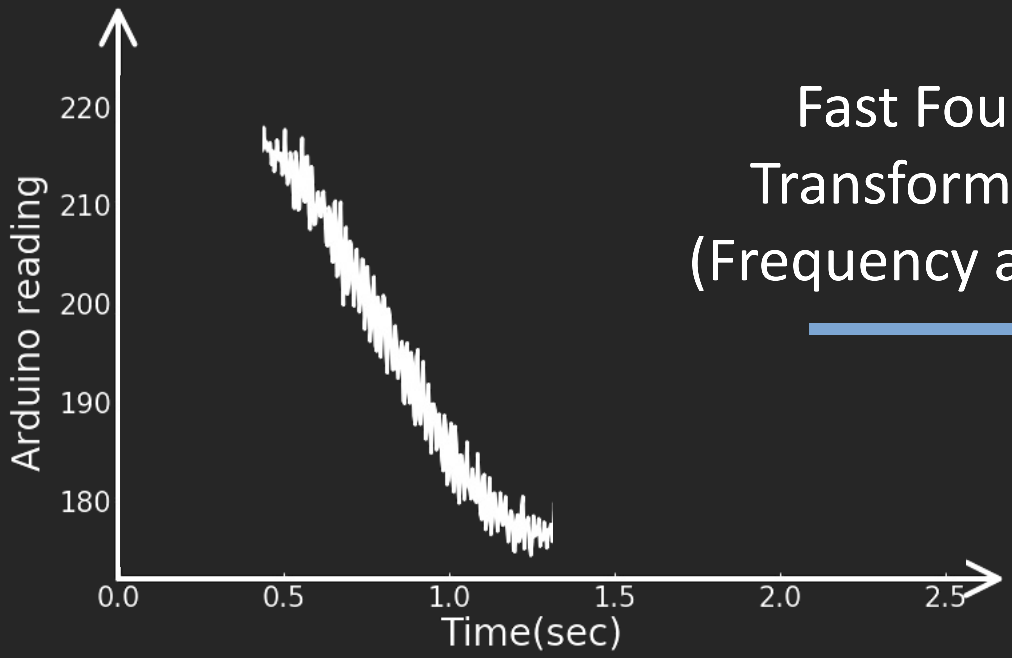

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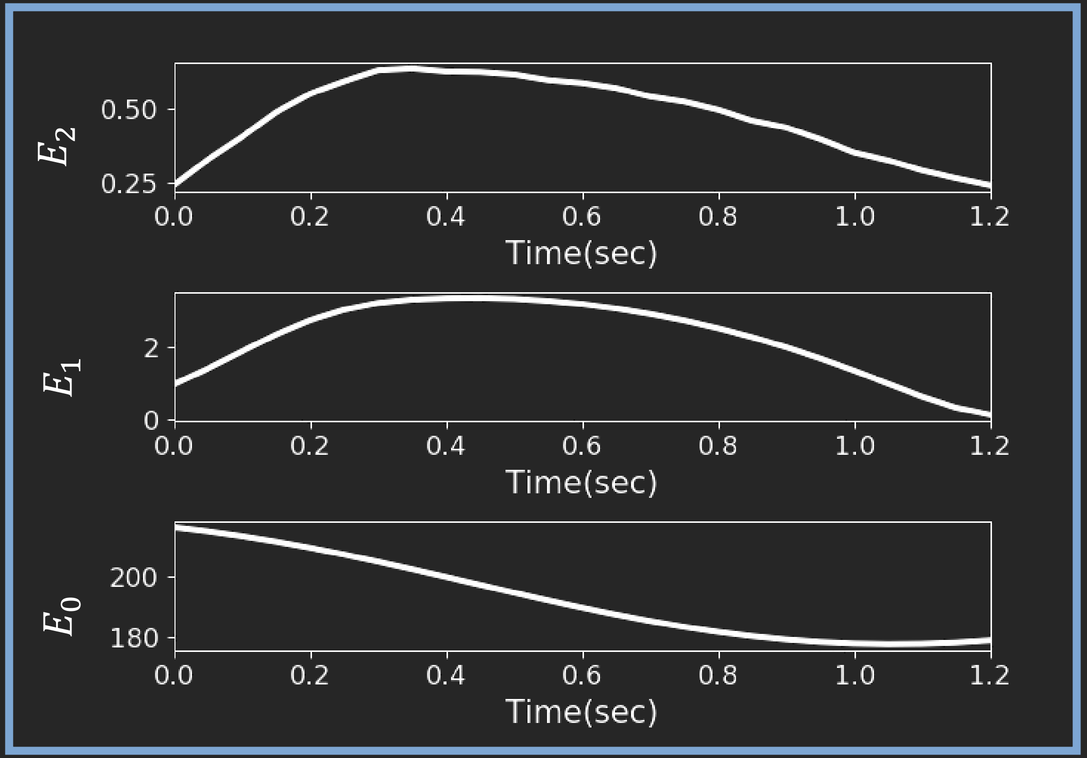
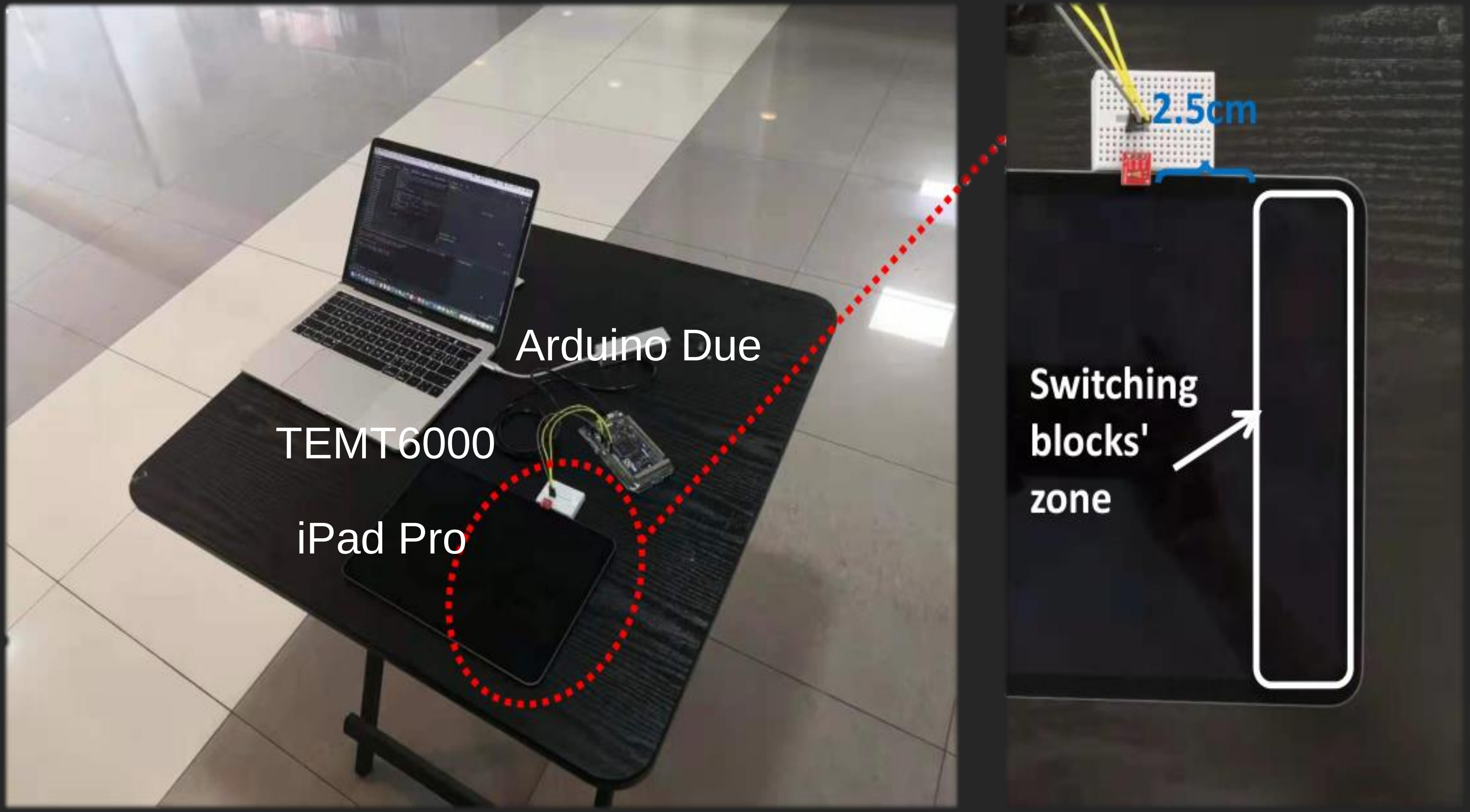


Feature extraction & Classification

Gesture recognition

Evaluation

- Prototype
  - Transmitter: iPad Pro 11;
  - Receiver: TEMT6000(250Hz); Arduino Due;
- Experiment setting
  - 9 gestures;
  - 8 users;
  - 5 static & 2 dynamic lighting environments;



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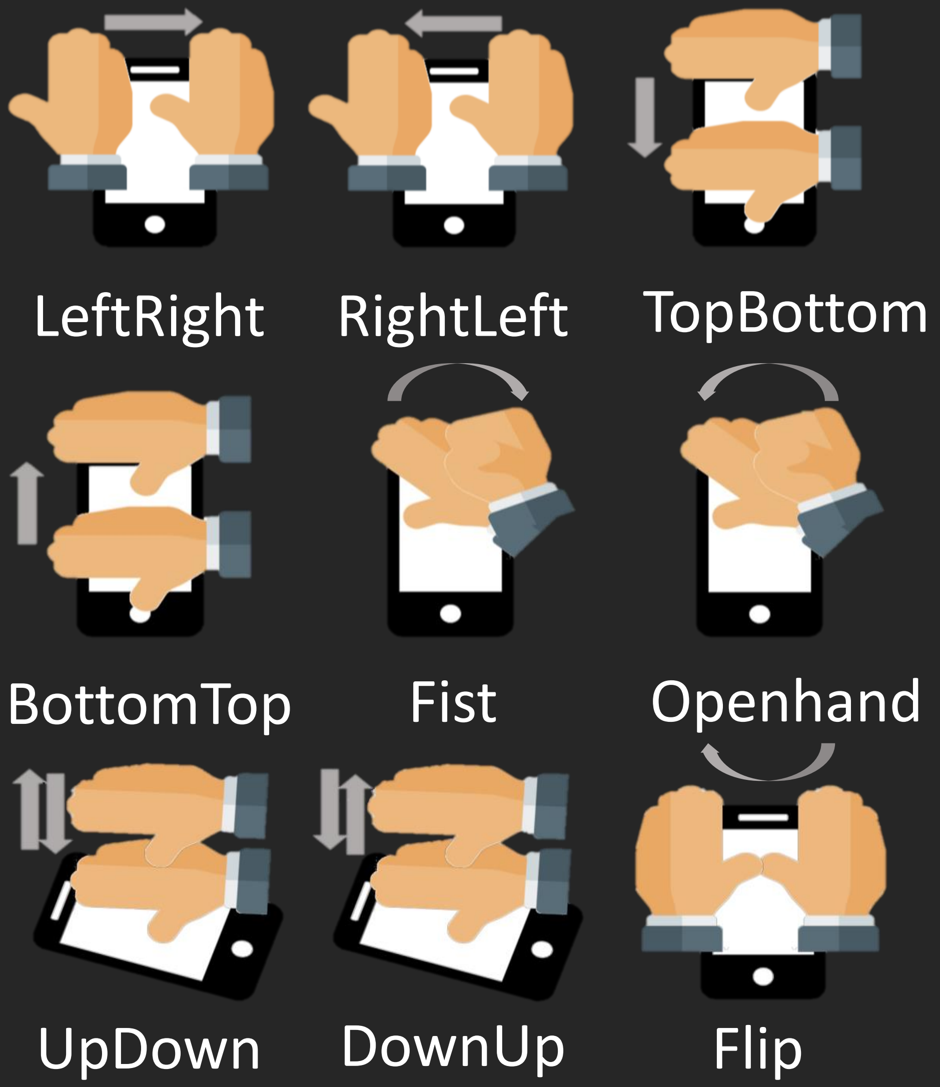
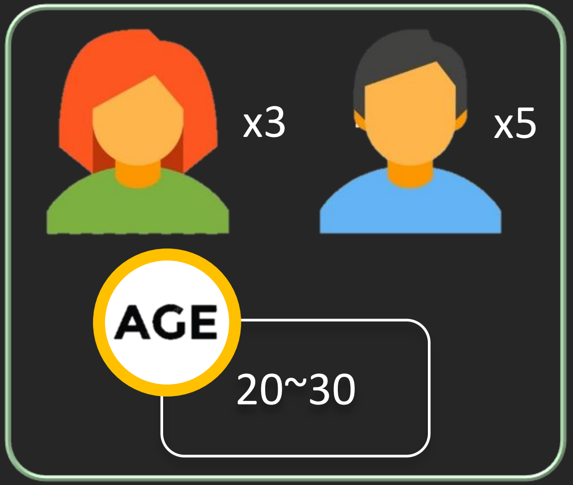
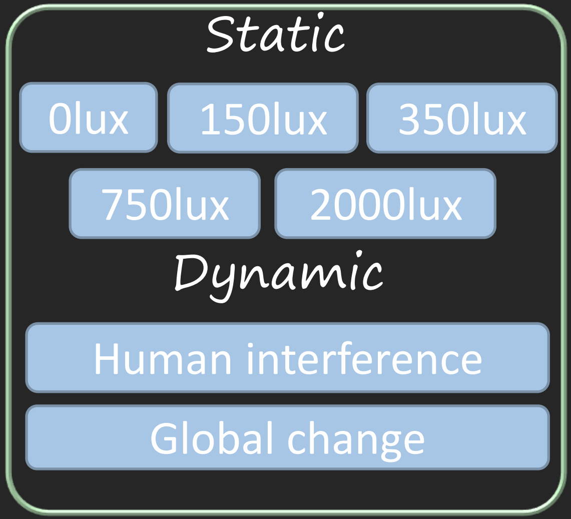






Static

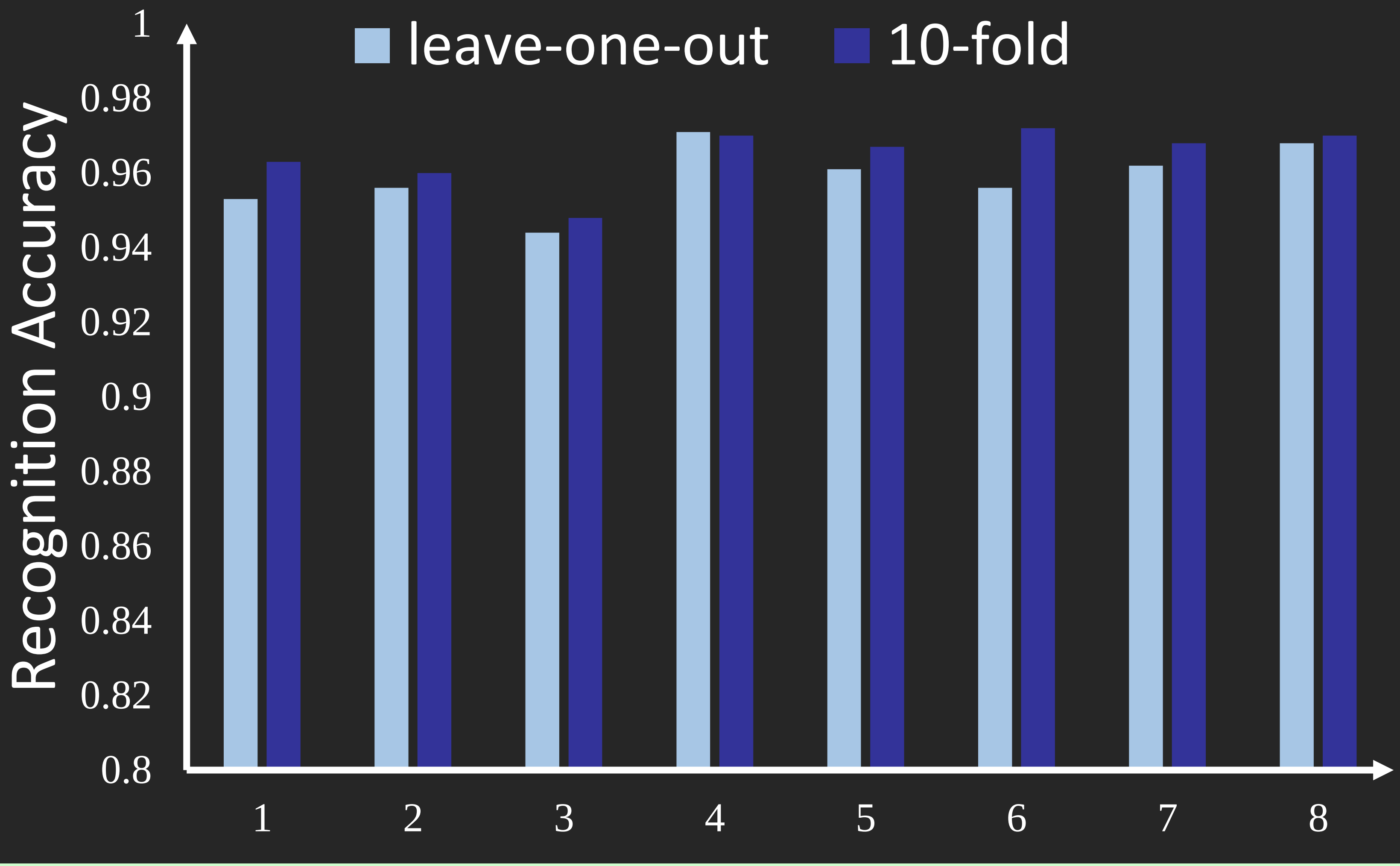
0lux | 150lux | 350lux | 750lux | 2000lux

Dynamic

Human interference

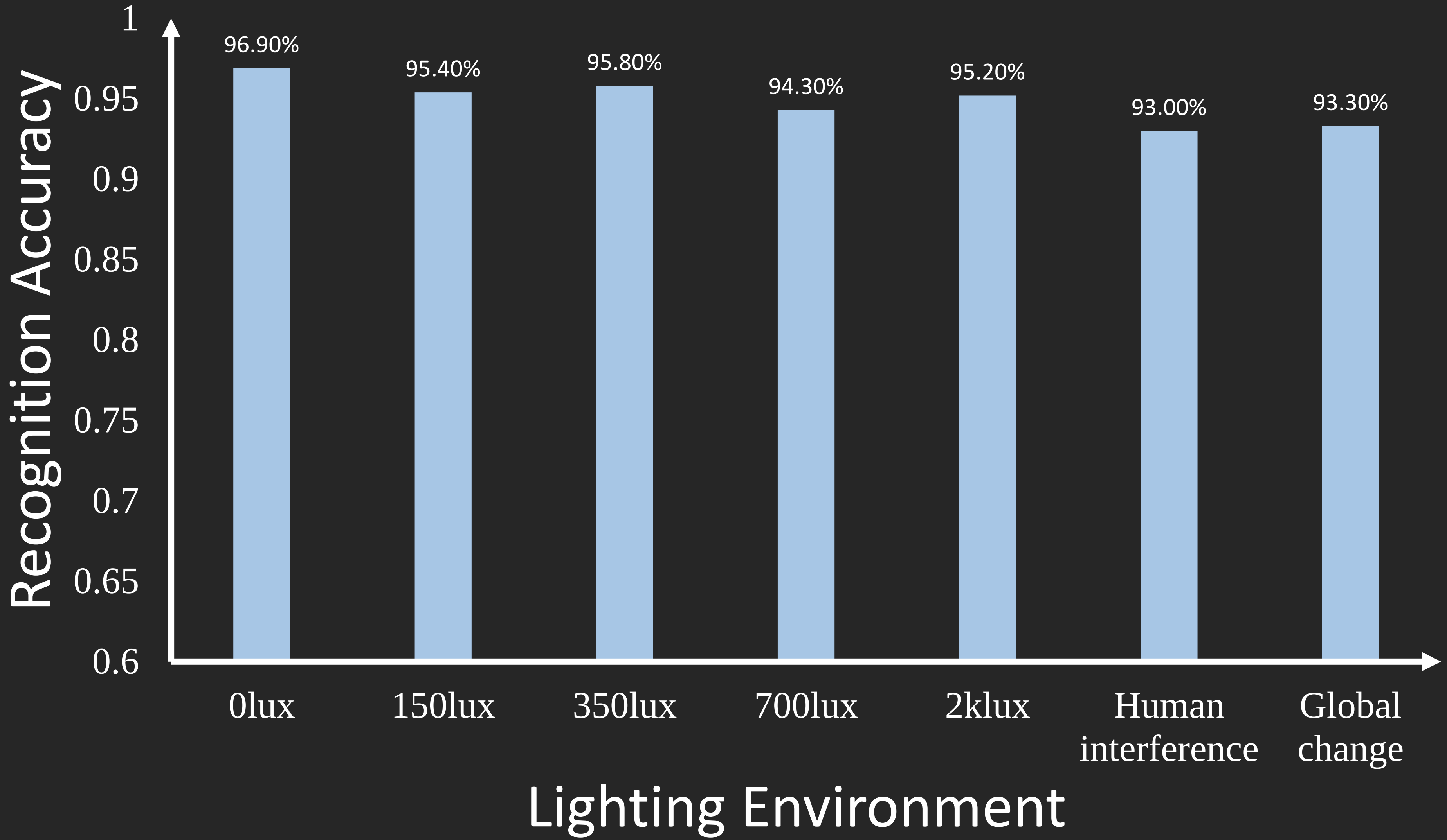
Global change

Accuracy v.s. Different users

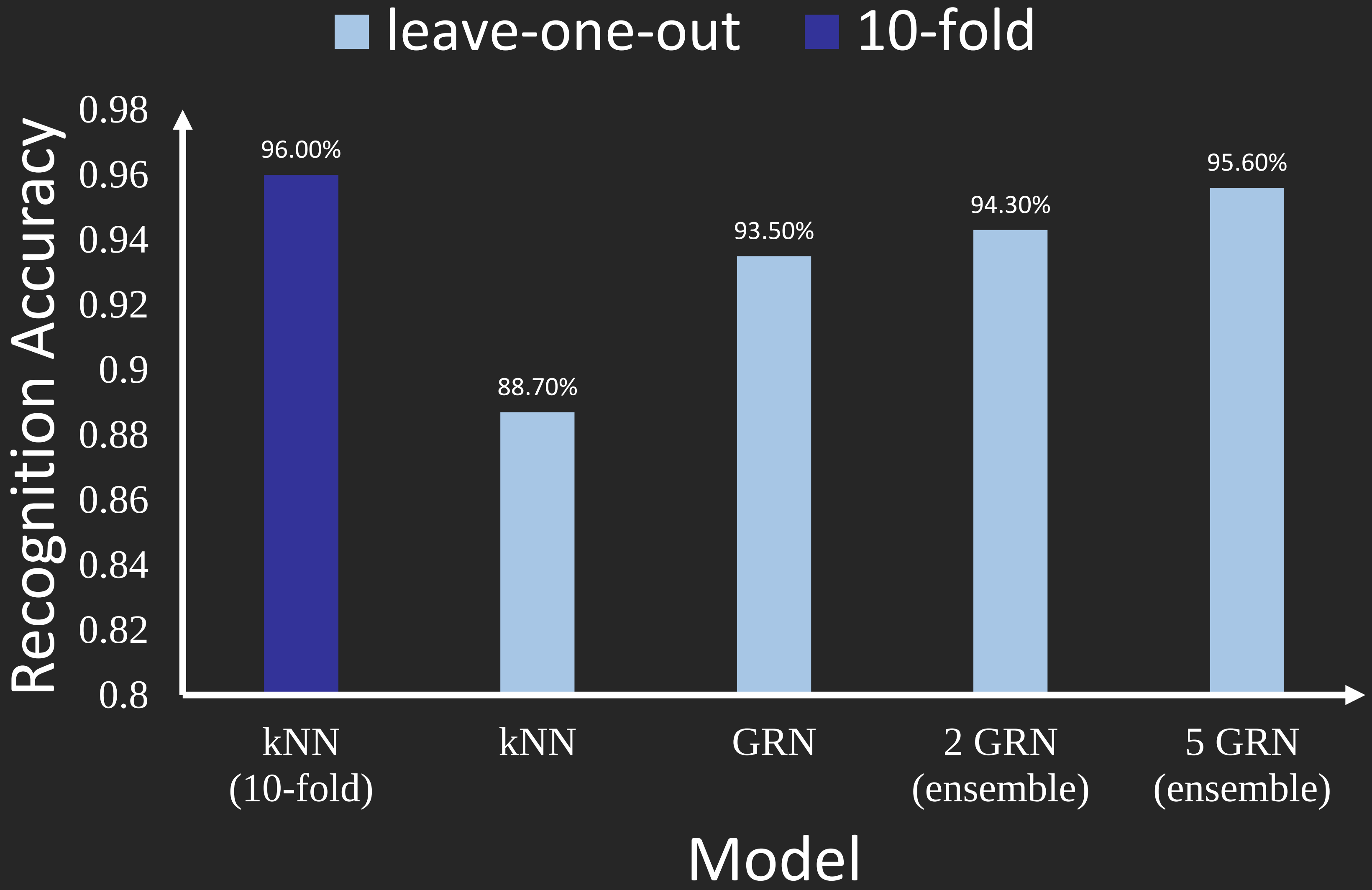


SMART is a generic model.

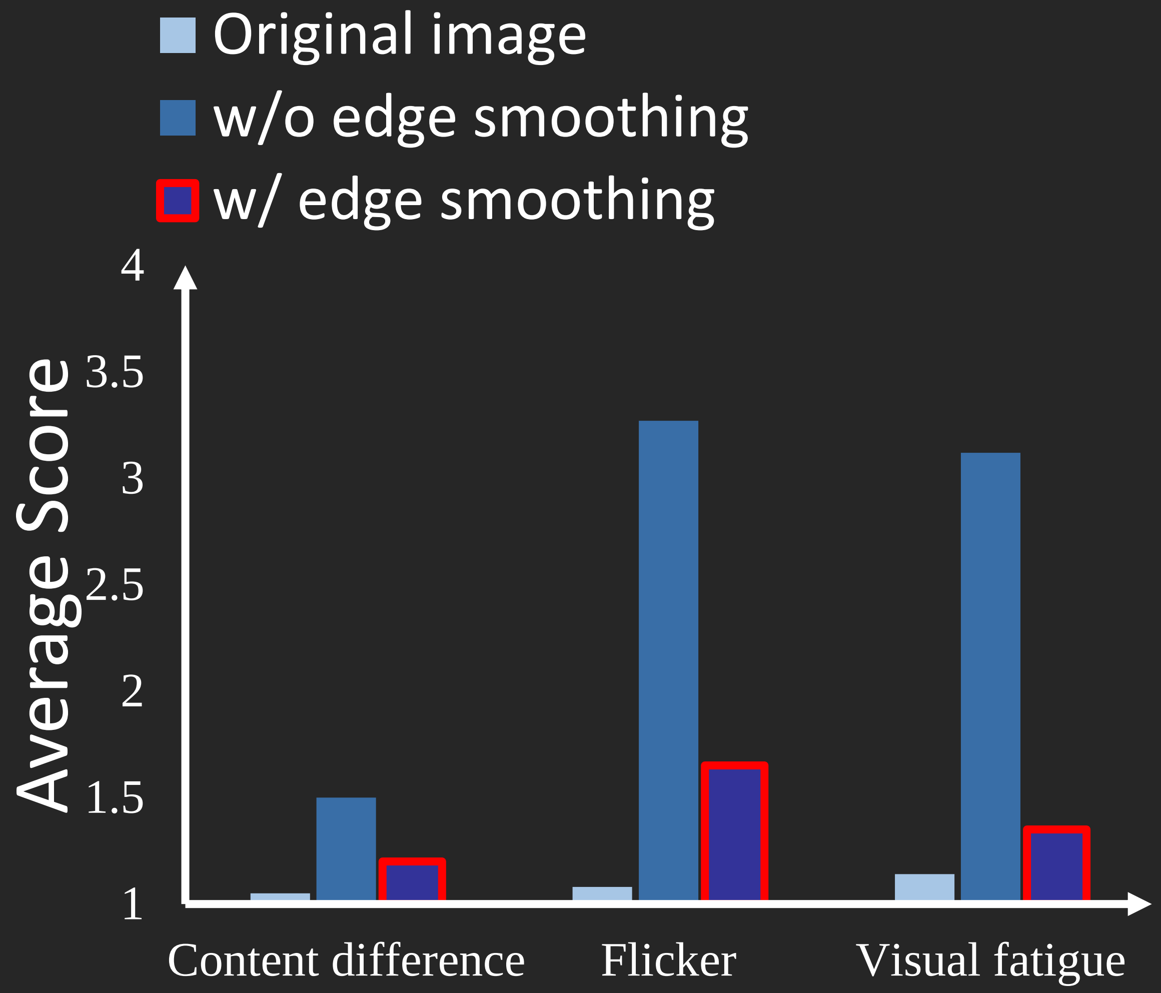
Accuracy v.s. Different lighting environments



Accuracy v.s. Unseen lighting environments



User perception

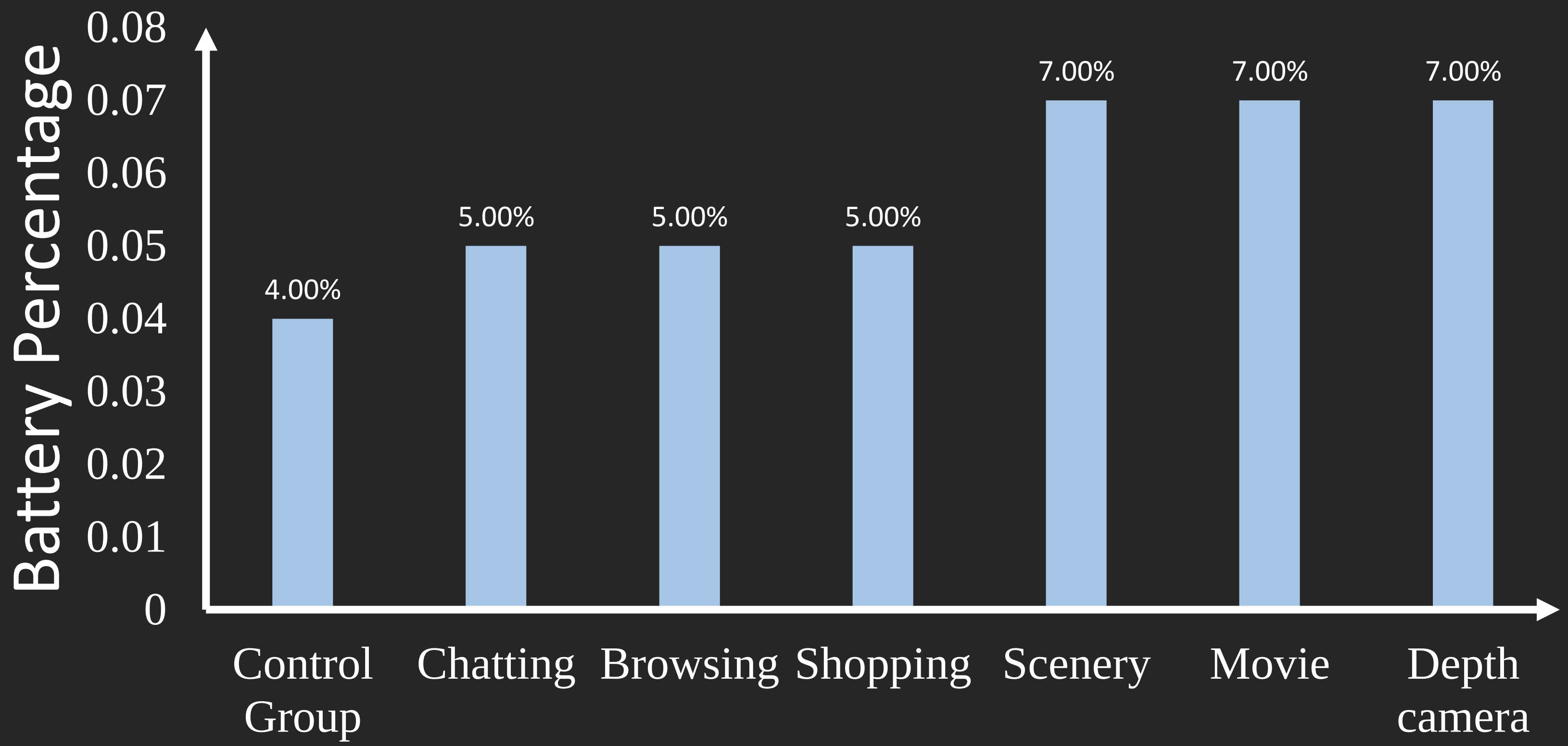


15 volunteers, 6 different images

Score	Content difference	Flicker	Visual fatigue
1	The same	No flickering	No fatigue
2	↓	↓	↓
3			
4	Evidently different	Evident flickering	Strong fatigue

Power consumption comparison with depth camera

Huawei
Mate30 Pro



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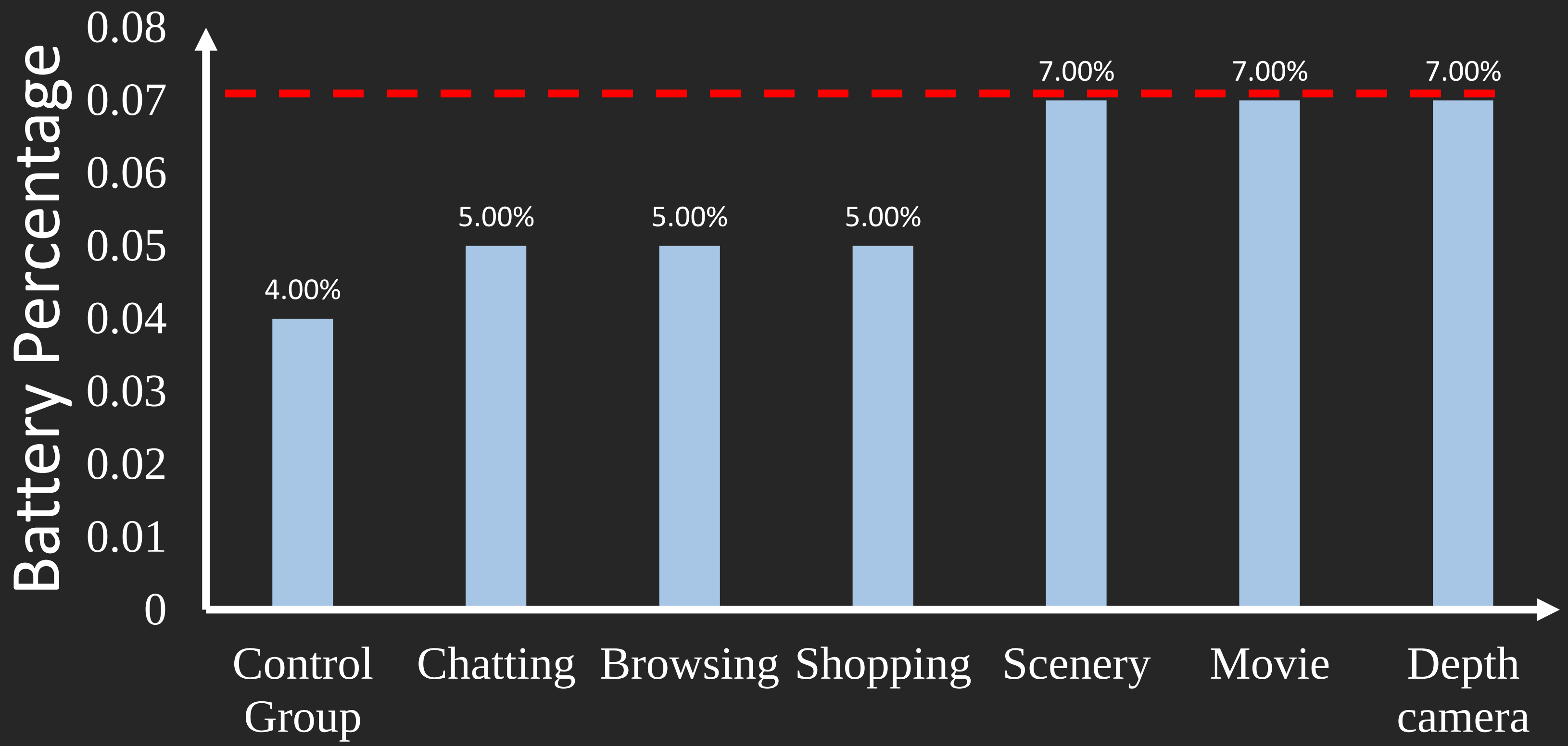

SMART's power consumption is lower than depth-camera

Thanks for your attention!

Q&A