# Communication and Sensing Using Light

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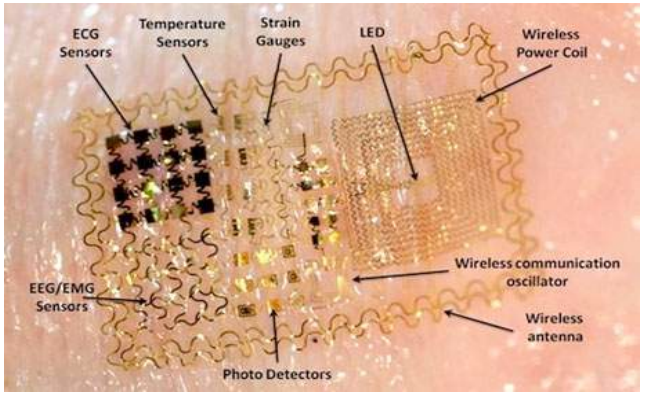
dartnets

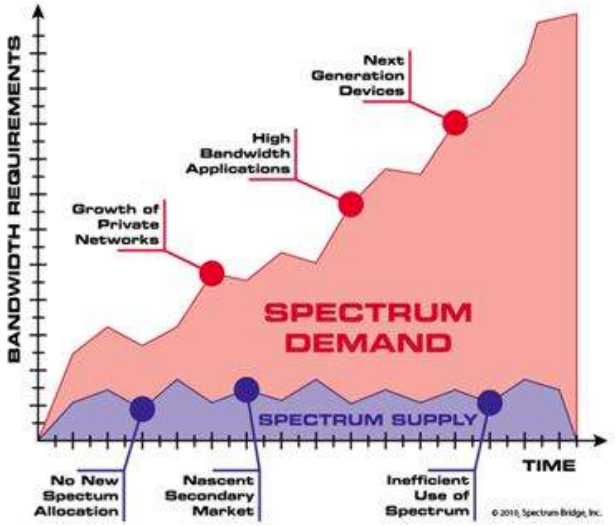
# Increasingly Connected World



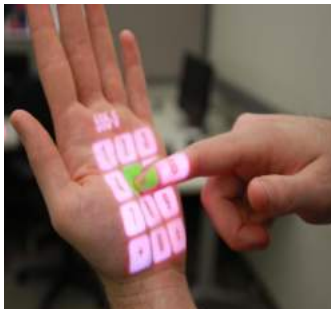


# Two Key Challenges Emerge

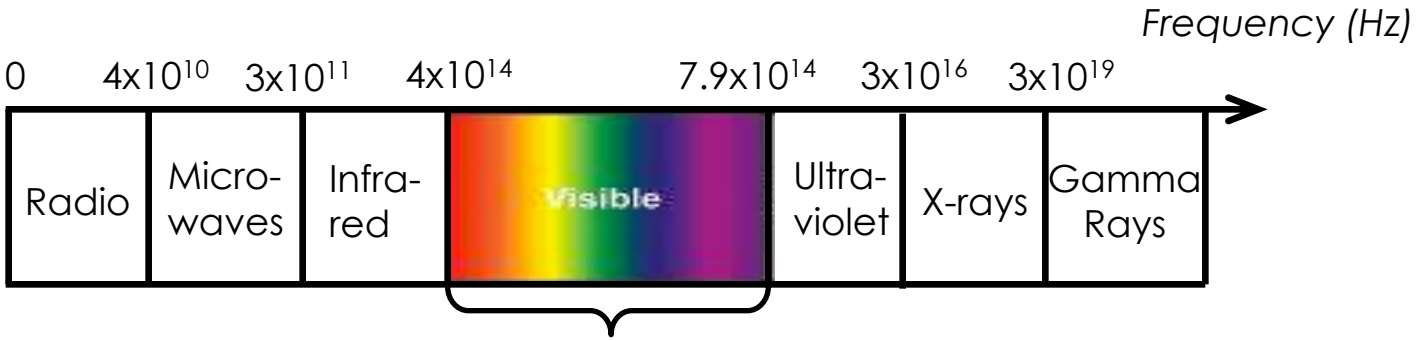
- Radio spectrum crunch
  - Ever-growing user demands meet limited radio spectrum




- Interaction with diverse smart devices

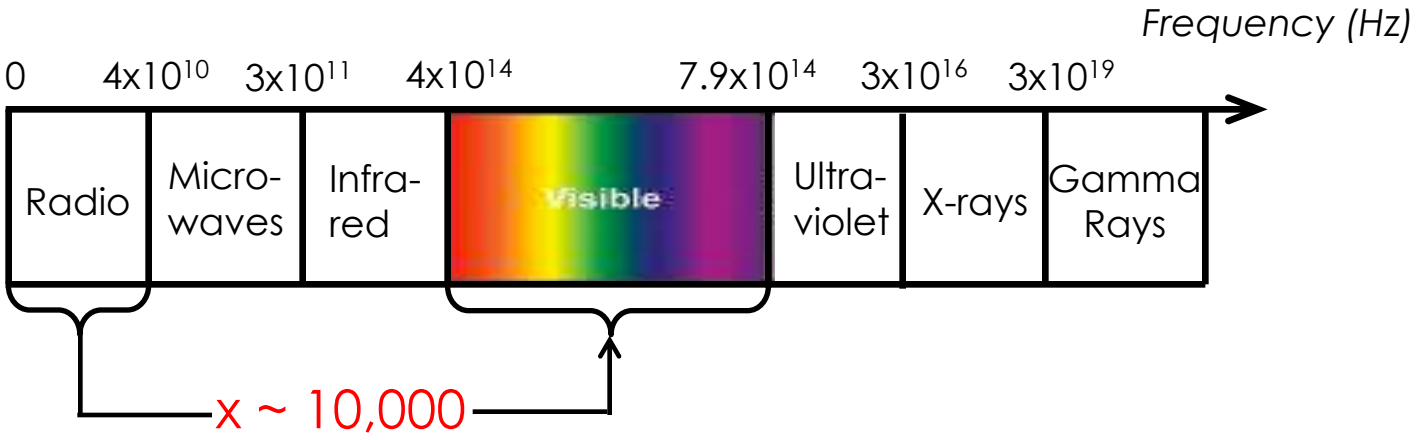


# Looking into the Visible Light Spectrum




390 nm – 700 nm in wavelengths
430 – 770 THz in frequency

# Looking into the Visible Light Spectrum




## Key Benefits

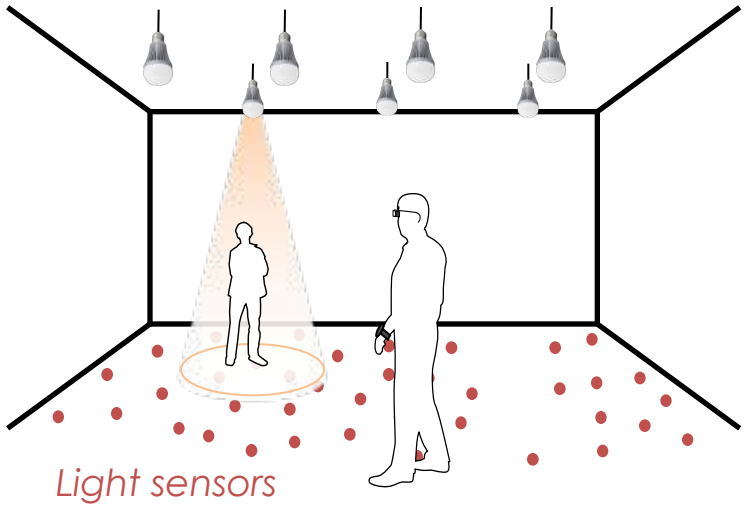
- ~400THz free bandwidth
- Free of electromagnetic interference
- Ubiquitous
- Energy-efficient
- Secure

# Light as a medium that integrates communication and sensing

# Roadmap

## Visible Light Communication

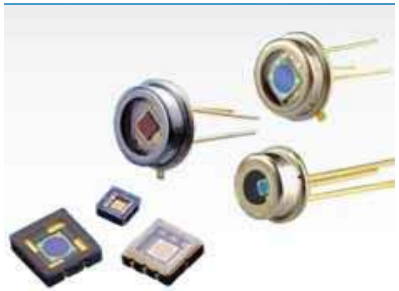
## Visible Light Sensing



# Visible Light Communication

**Encode data into light intensity changes of Light Emitting Diodes (LEDs)**

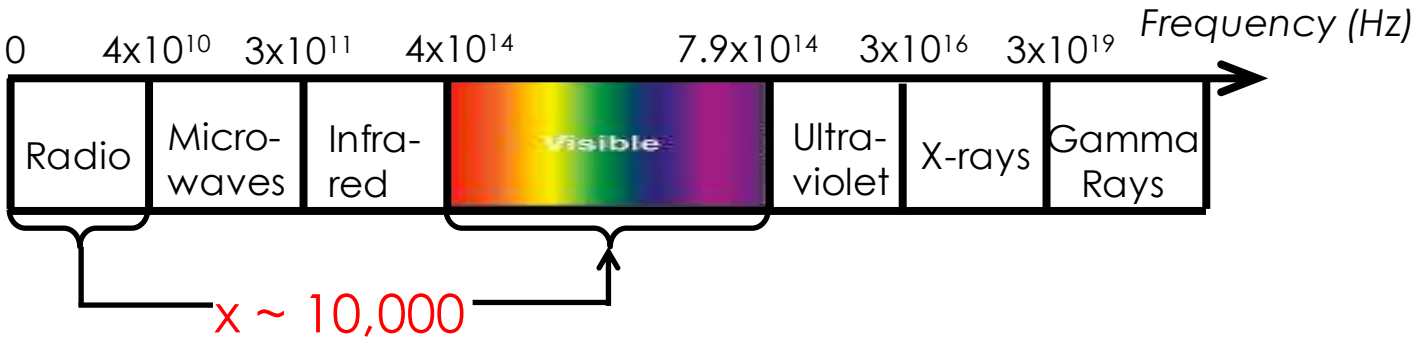
Eyes cannot detect fast light switching,
but semiconductor-based photodetector can!



# Key Differences From RF

#1: RF communication can modulate frequency or phase of the carrier

Light uses **Intensity modulation and direct detection (IM/DD)**




10K wider bandwidth ≠ 10K higher data rates

# Key Differences From RF

#2: Tight coupling of illumination

Cannot affect light illumination (avoid flickering, > 1KHz)

# Discussion: What's your idea to enable light communication?

# VLC Modulation Schemes

- On-off keying (OOK)
- Frequency-shift keying (FSK)
- Pulse amplitude modulation (PAM)
- Pulse width modulation (PWM)
- Pulse position modulation (PPM)
- Color shift keying (CSK)
- Spatial keying
- Polarization based modulation
- OFDM (ACO-OFDM, DCO-OFDM)
- Your design? ☺

# Inherent Challenges

**Blockage**

**Distance**

**Uplink**


**Lights not always on**

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**Blockage**

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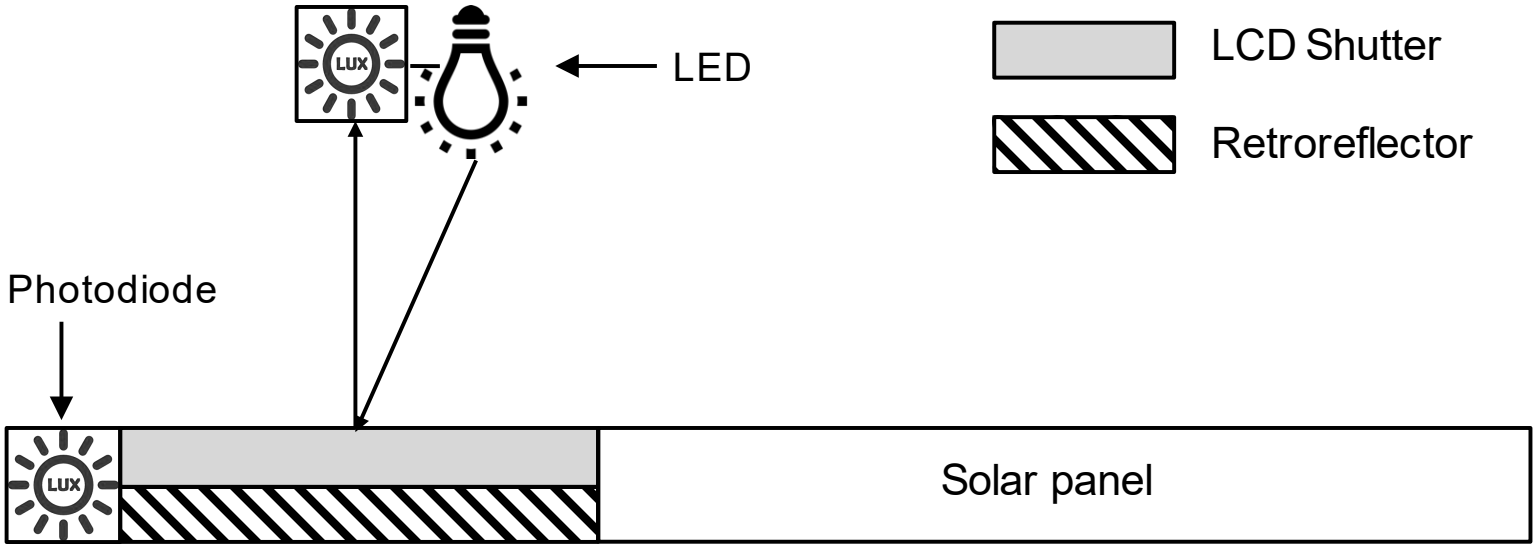
# RetroVLC




- Retro-VLC: Enabling Battery-free Duplex Visible Light Communication for Mobile and IoT Applications. HotMobile'15.
- PassiveVLC: Enabling Practical Visible Light Backscatter Communication for Battery-free IoT Applications. MobiCom'17.

# Inherent Challenges

**Blockage**

**Distance**

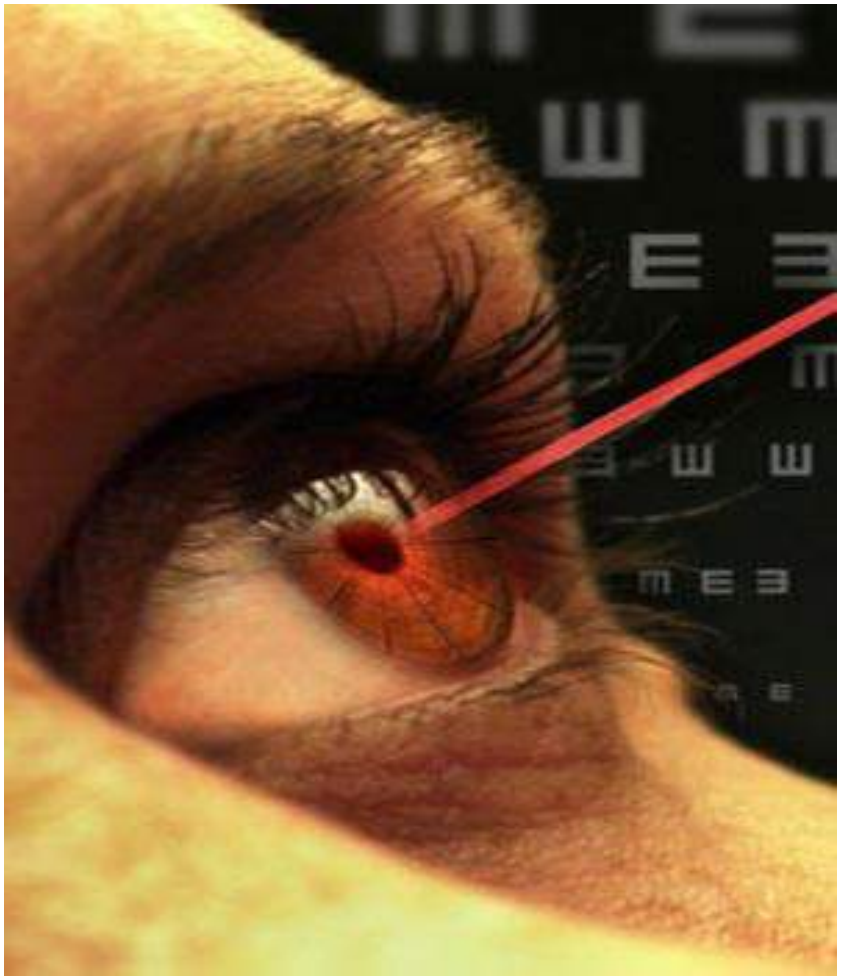
**Uplink**

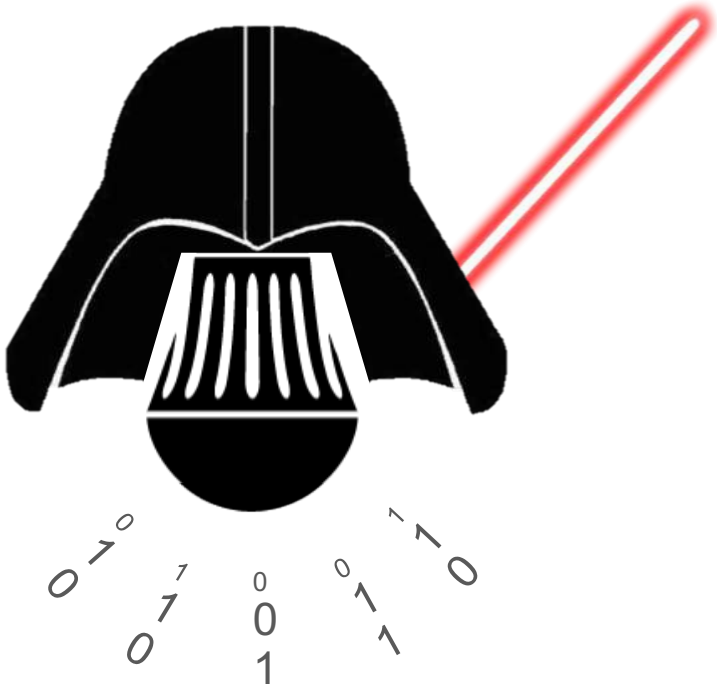

**Lights not always on**

# How about Infrared?

Need infrared emitters

Eye-safety issues





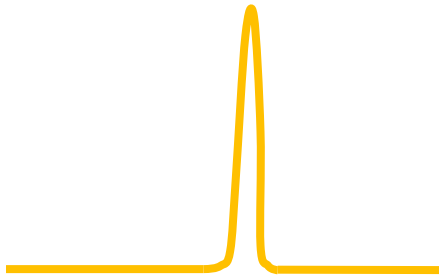

DARKLIGHT

Video link: https://youtu.be/qwxLYC2z1C0

# DarkLight: Key Idea

Encode data into ultra-short light pulses

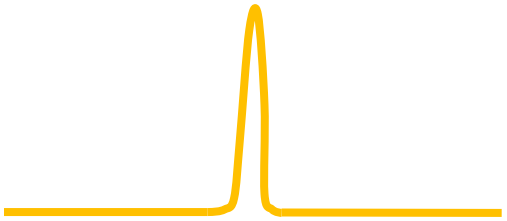
LED



Eyes

- Low temporal resolution
- Accumulative

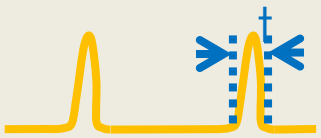




Photodiodes

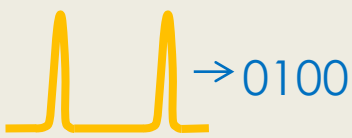
- High temporal resolution

# Challenges




Ultra-short Light Pulses

- *Off-the-shelf LEDs*
- *Low-cost photodiodes*



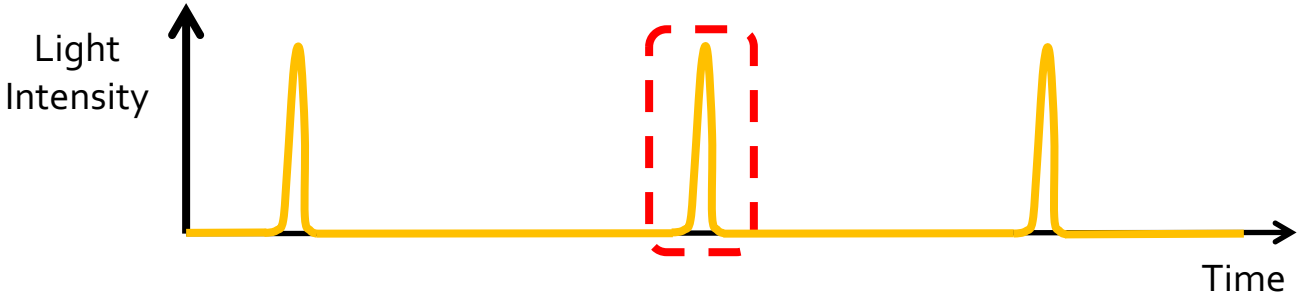

Data Encoding and Decoding

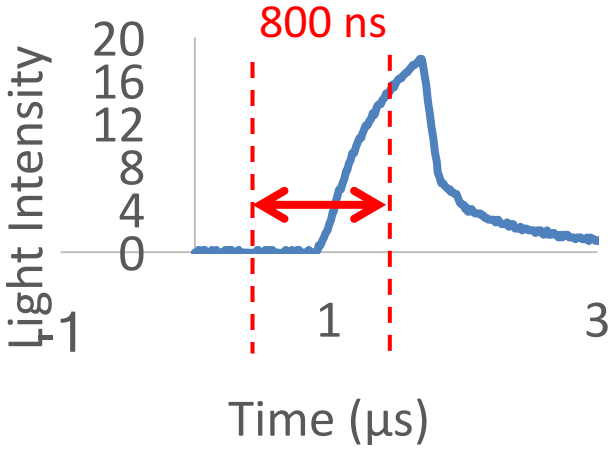
- *Extremely low duty cycle*
- *Ambient light variation*

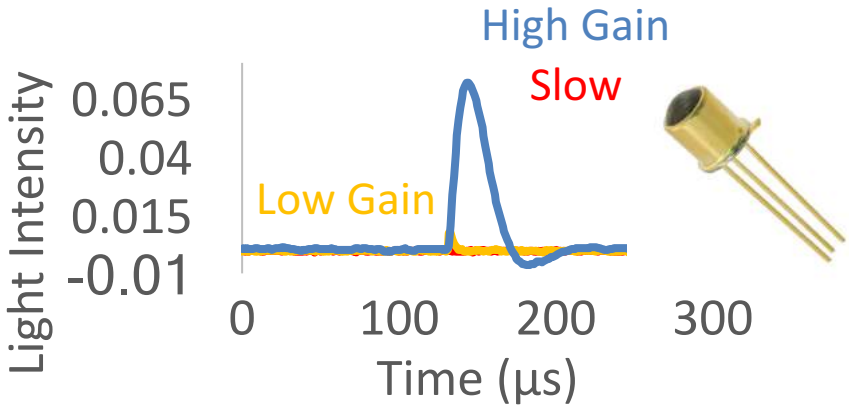

Multiple Transmitters

- *Pulses interfere at the receiver*

# #1: Dealing with Ultra-Short Light Pulses



# Efficient Circuit Design

FPGA

LED: CREE
CXA 2520 ($7)

V=36V

Gate Driver

MOSFET

Photodiode: Honeywell SD 5421 ($6)

Transimpedance Amplifier

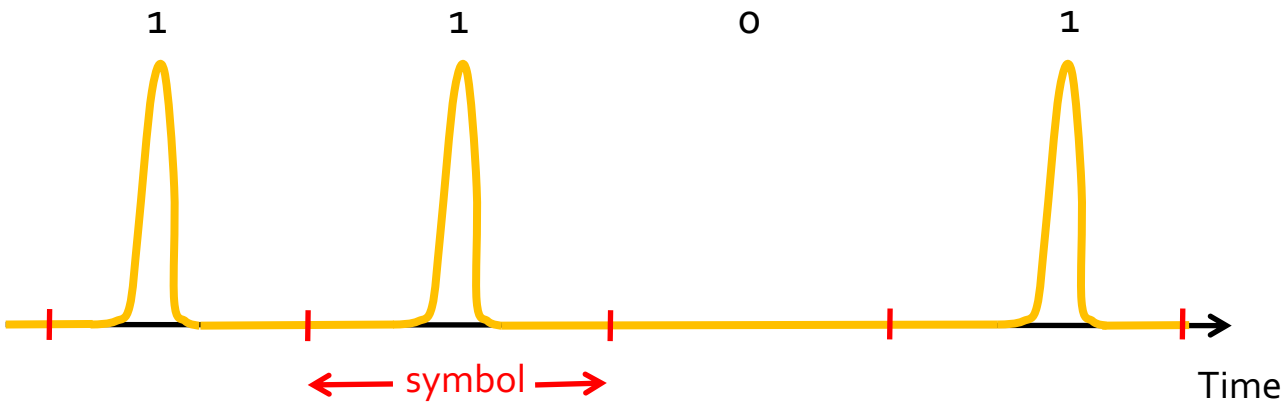
USRP

Can be replaced by

Dedicated ADC

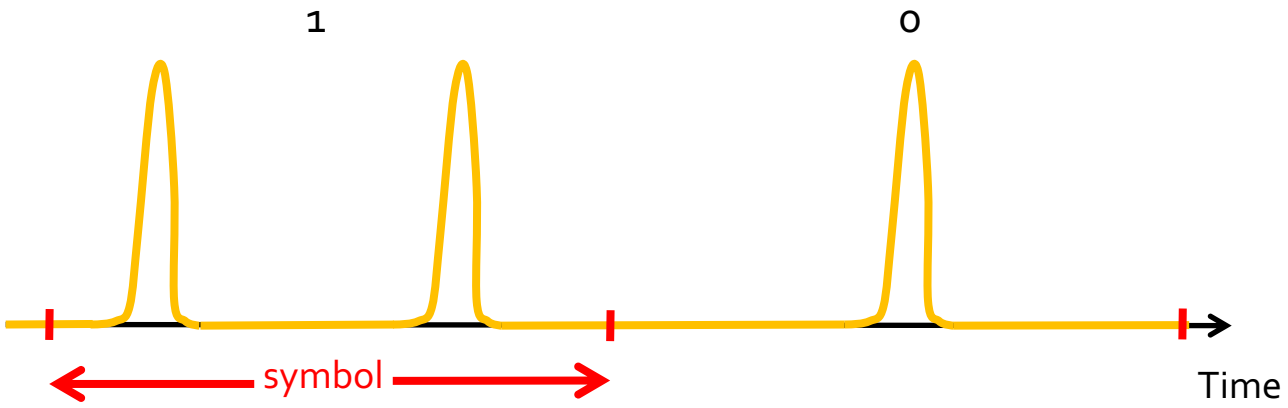
# #2: Data Encoding and Decoding

- OOK: 1 bit per pulse (~190 bps)



# #2: Data Encoding and Decoding

- OOK: 1 bit per pulse (~190 bps)
- FSK: multiple pulses encoding 1 bit (~160 bps)

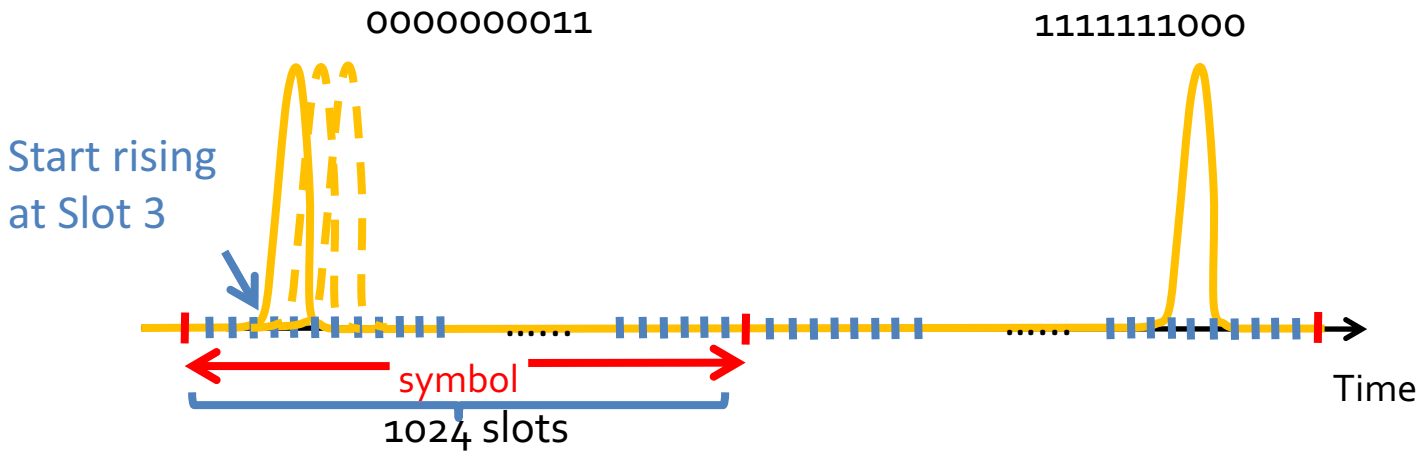


# Encode Data Efficiently

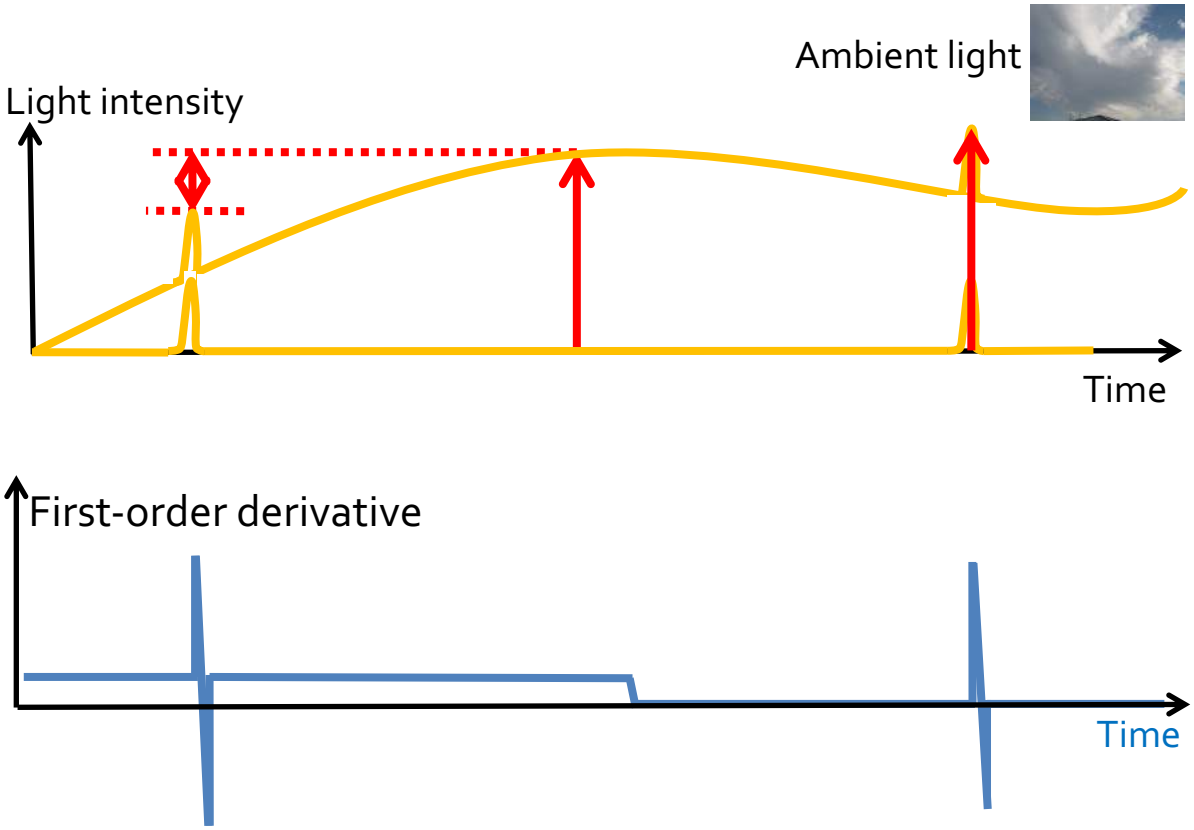
- OOK: 1 bit per pulse (~190 bps)
- FSK: multiple pulses encoding 1 bit (~160 bps)
- Our design:

**Overlapping Pulse Position Modulation (OPPM)**

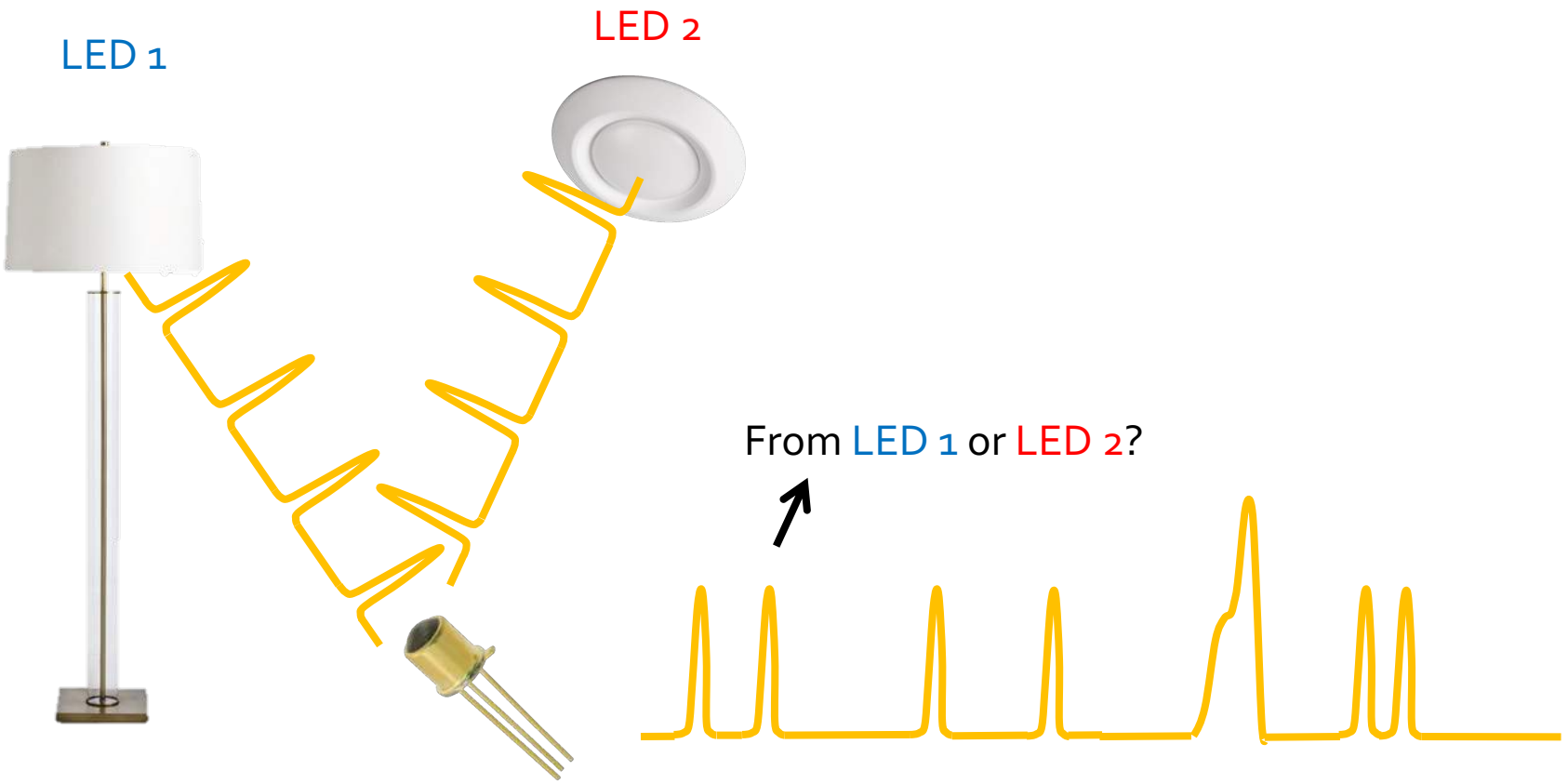
10 bits/symbol



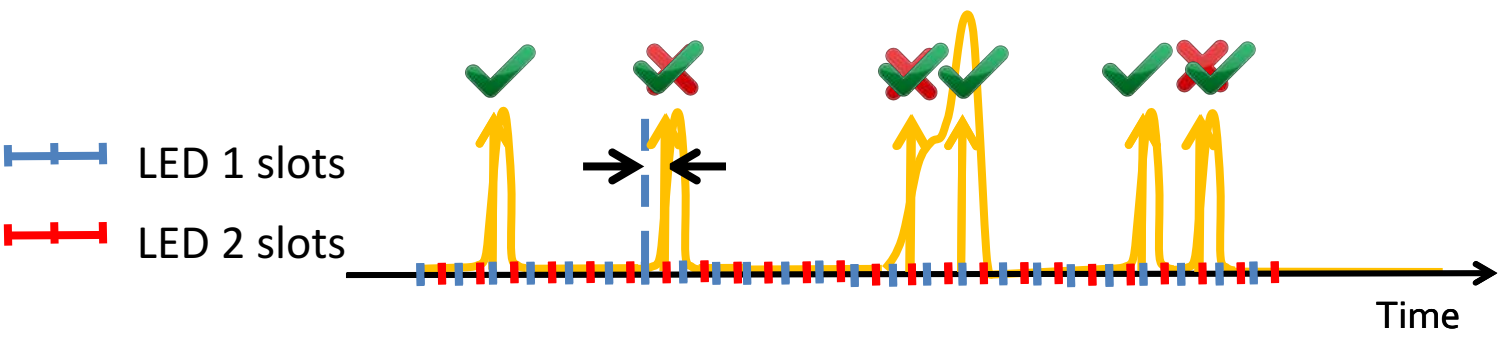
# Detect Pulses Reliably



# #3: Multiple Transmitters



# Identifying Pulse Sources

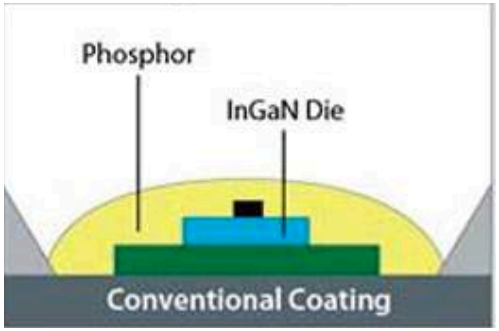



LED 1 Pulses

LED 2 Pulses

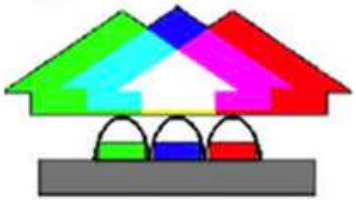
# Open Research Challenges

- Limit of existing LED luminaries




Blue LED + Yellow phosphor

**Lower modulation bandwidth**
**More efficient lighting**



RGB LED

**Higher modulation bandwidth**
**Less efficient lighting**

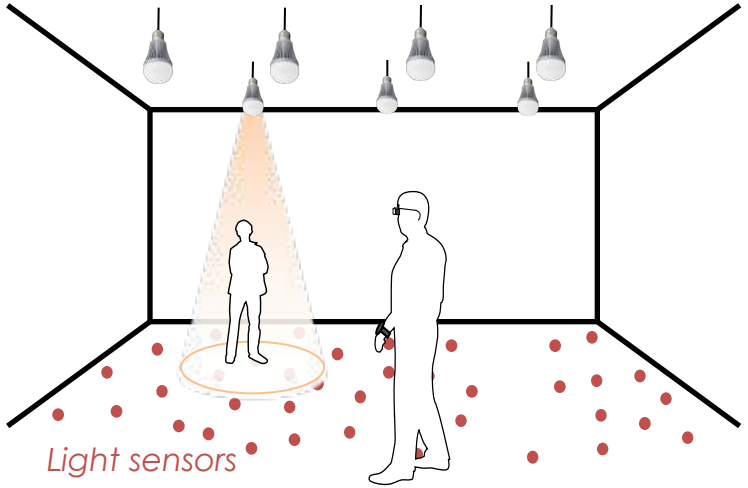
# Open Research Challenges

- Co-existence of other medium
- Power consumption of RX design
- Innovative application scenarios, diverse communication forms (e.g., screen to camera, LED to camera)

# Roadmap

## Visible Light Communication

## Visible Light Sensing



Occupancy detection

Gesture recognition

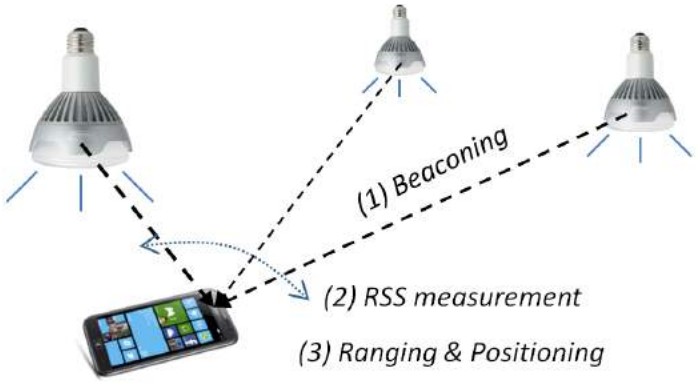
Activity estimation

Indoor localization

Skeleton pose estimation

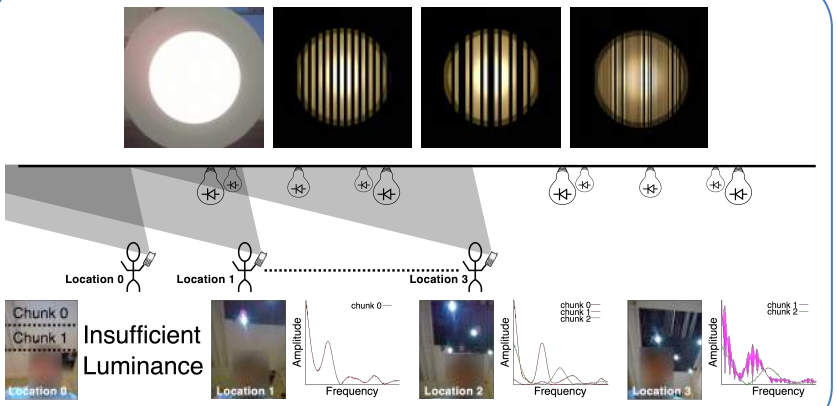
# Indoor Localization

## RSS-based [LHP+14]



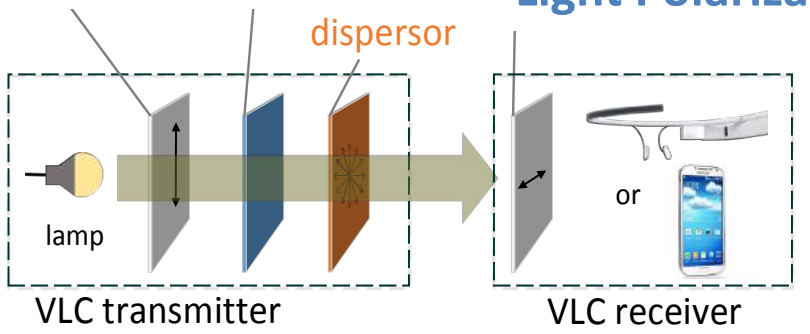

0.4m accuracy

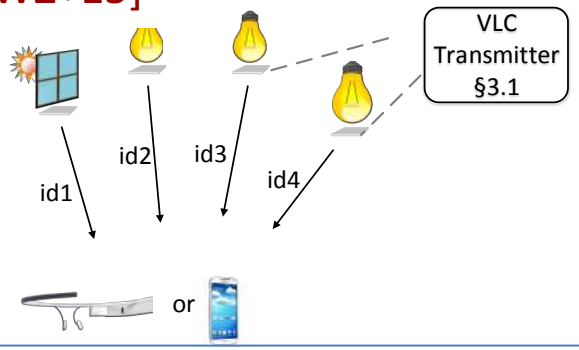
## Pattern-based [KPH+14]




0.1m accuracy

## Light Polarization [YWZ+15]

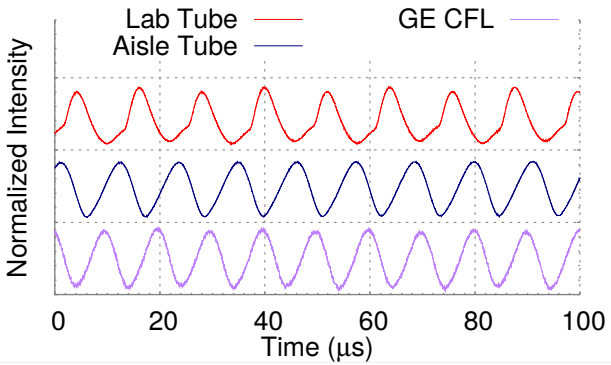


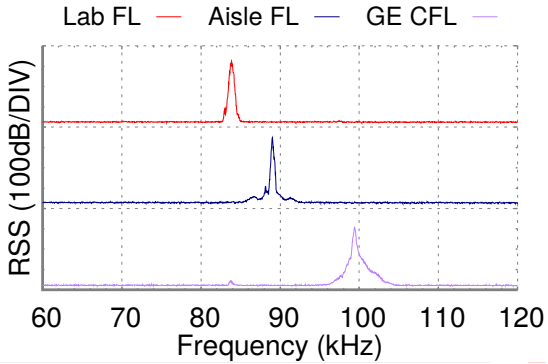



# Indoor Localization

## Exploiting Light inherent feature

### Light's Characteristic Frequency



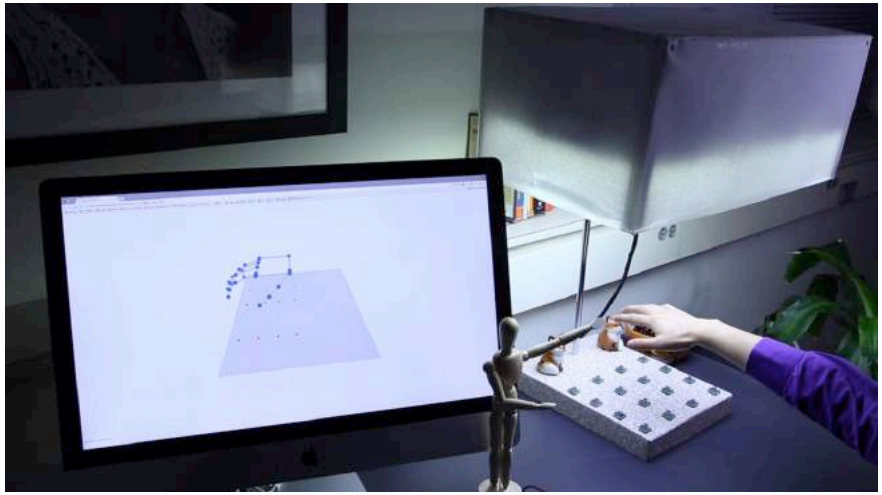

- Camera-based under fluorescent lights (LiTell, MobiCom'16)
- Camera-based under LED + fluorescent lights (iLAMP, MobiSys'17)
- Photodiode-based under LED + fluorescent lights (Pulsar, MobiCom'17)

# Skeleton Pose Estimation

**LiSense**

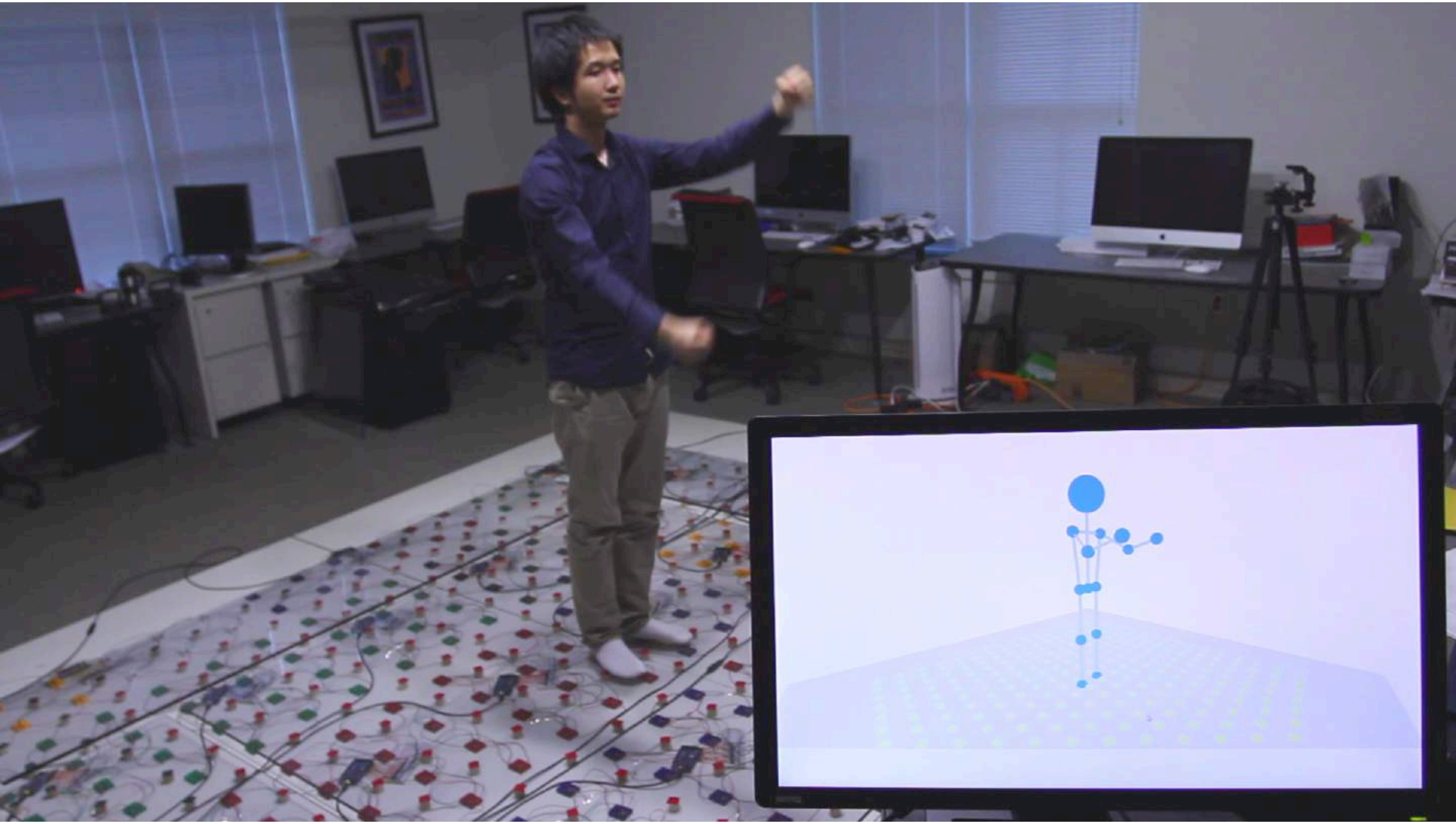
**StarLight**

**Aili**



**Minimalist Sensing**:
Replacing cameras with low-end, distributed photodiodes


Video link: https://youtu.be/7wK-zo66GdY



Video link: https://youtu.be/7wK-zo66GdY

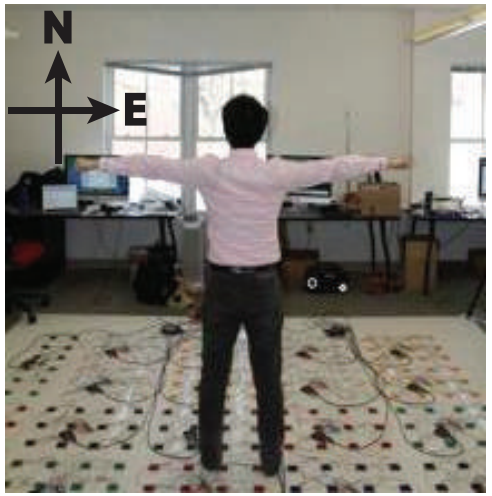
# Shadows!

# Not That Simple

**Challenge #1:** Diluted and complex shadow under multiple light sources

# Not That Simple

**Challenge #2:** Reconstruct a 3D posture from 2D binary low-resolution (18 x 18) shadows

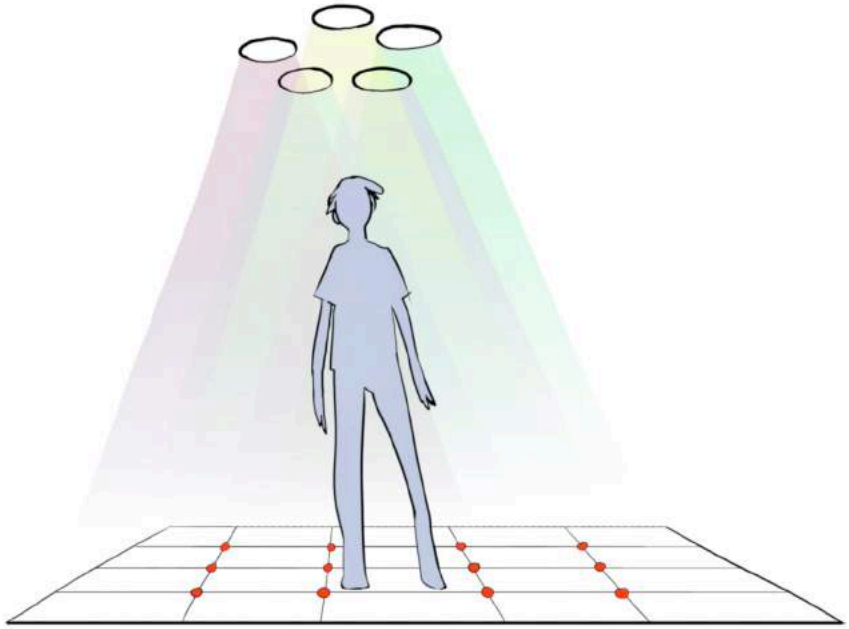


# LiSense Overview

Challenge #1:
Diminished shadow
under multiple lights

↓

Separate light rays via
light beacons

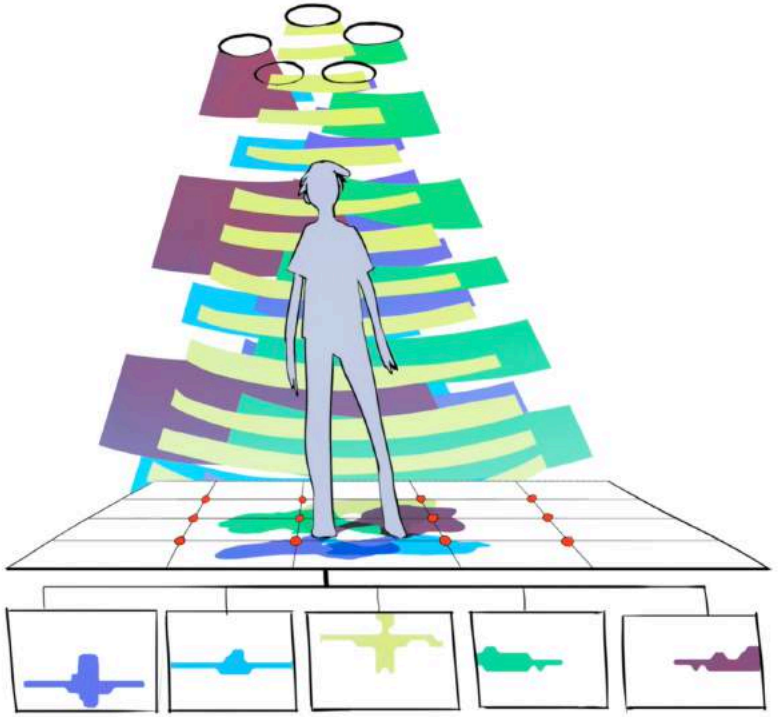


# LiSense Overview

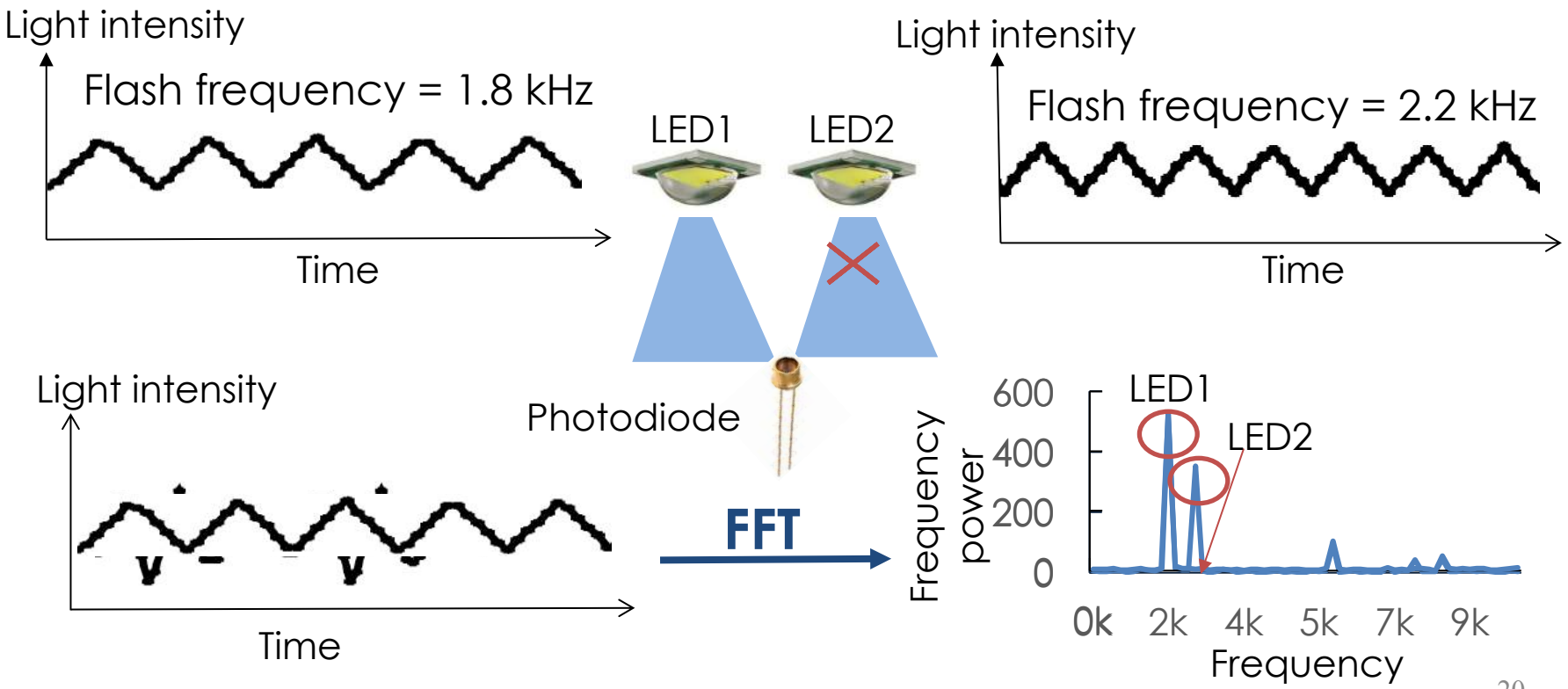
Challenge #2:
2D shadows → 3D posture

↓

Seek a posture best fitting shadows cast in multiple directions

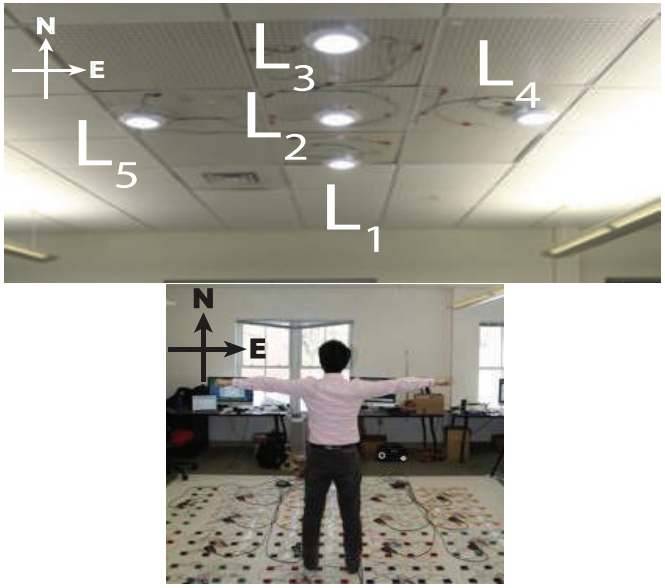


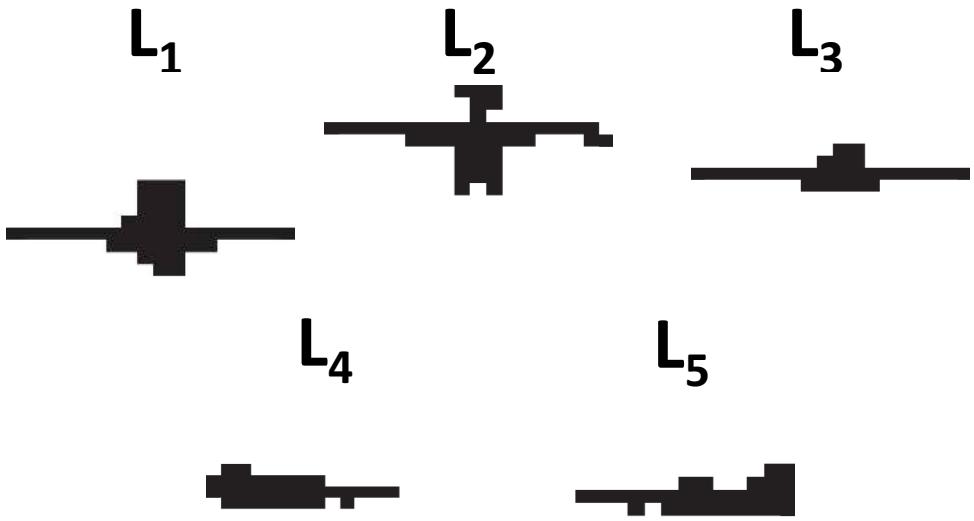
# Light Beacon Rationale



# Recovering Shadow Maps

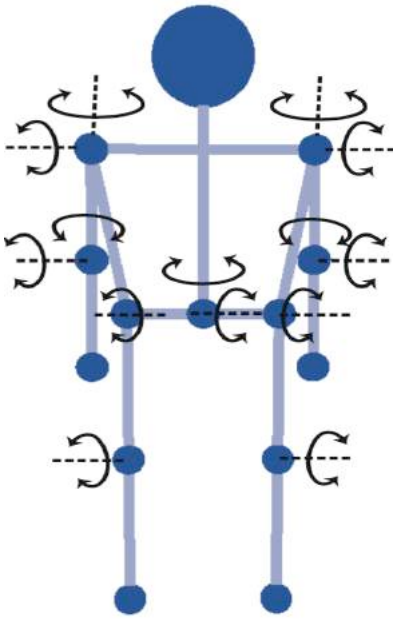
- Infer a binary shadow map cast by each single LED light



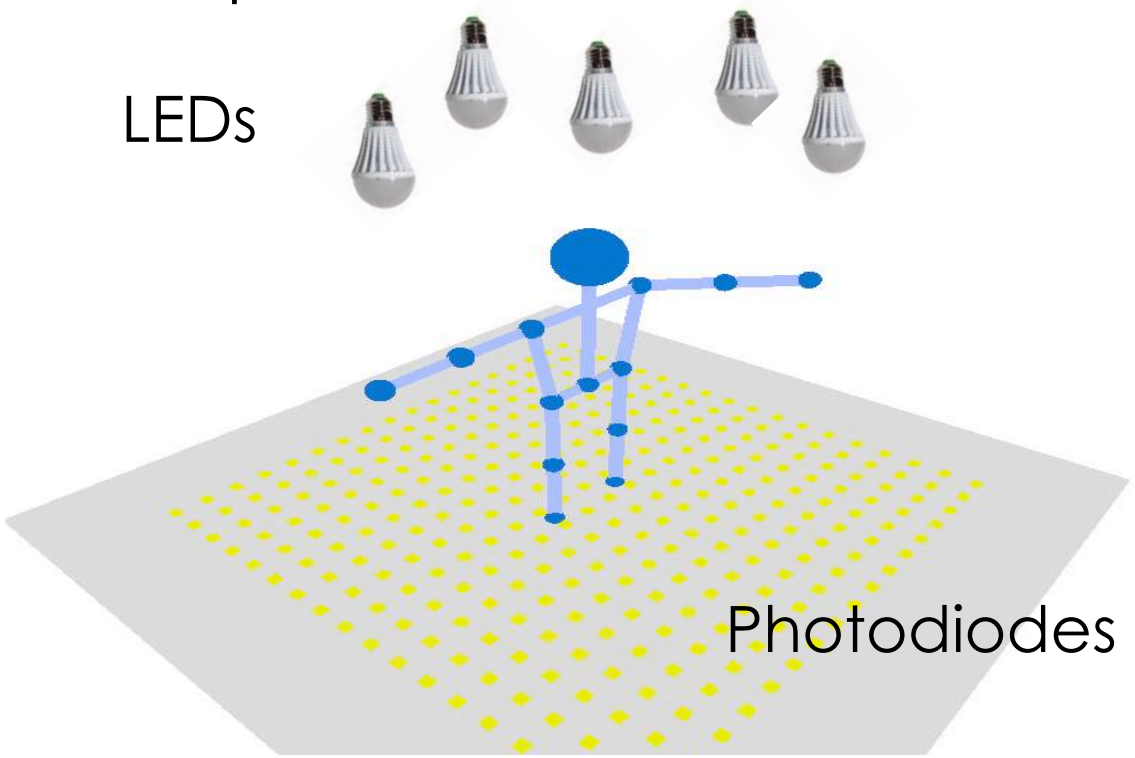
# Shadow-Based Inference

- Track nine key body joints



# Shadow-Based Inference

- Search for the skeleton best matching observed shadow maps



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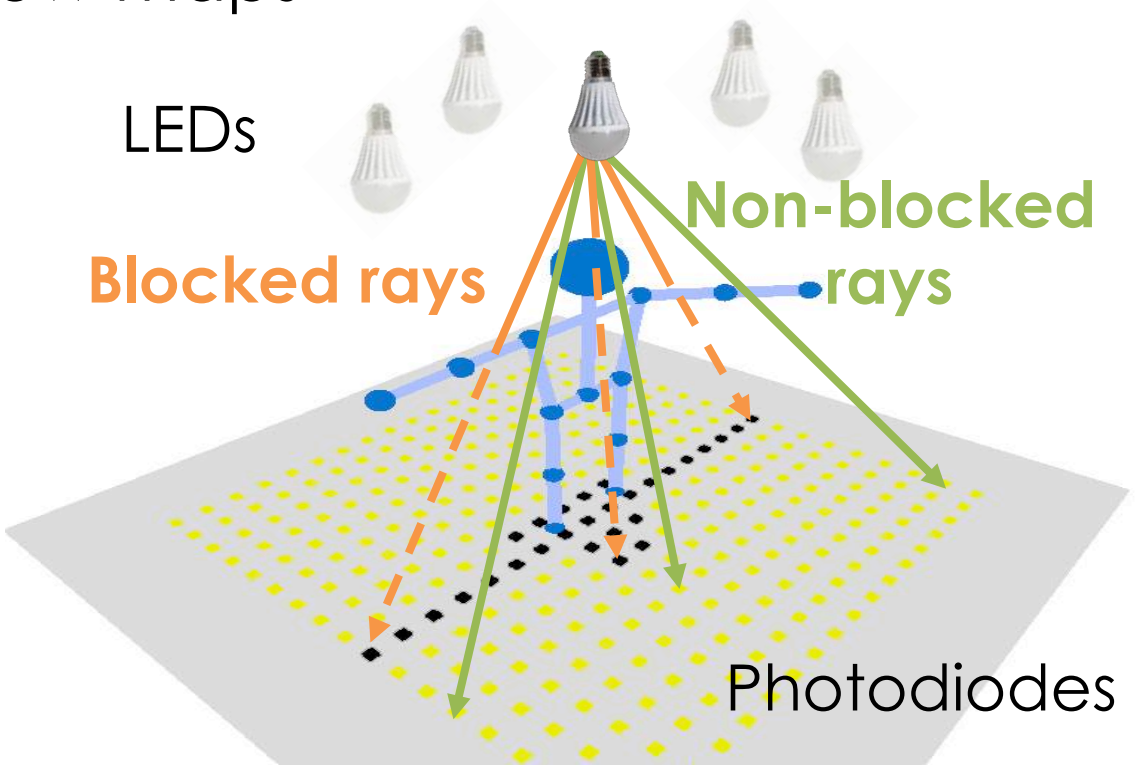
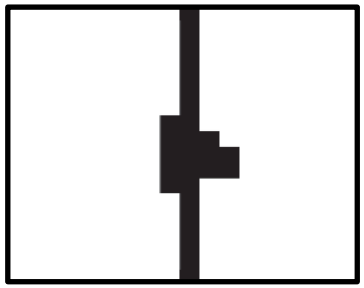
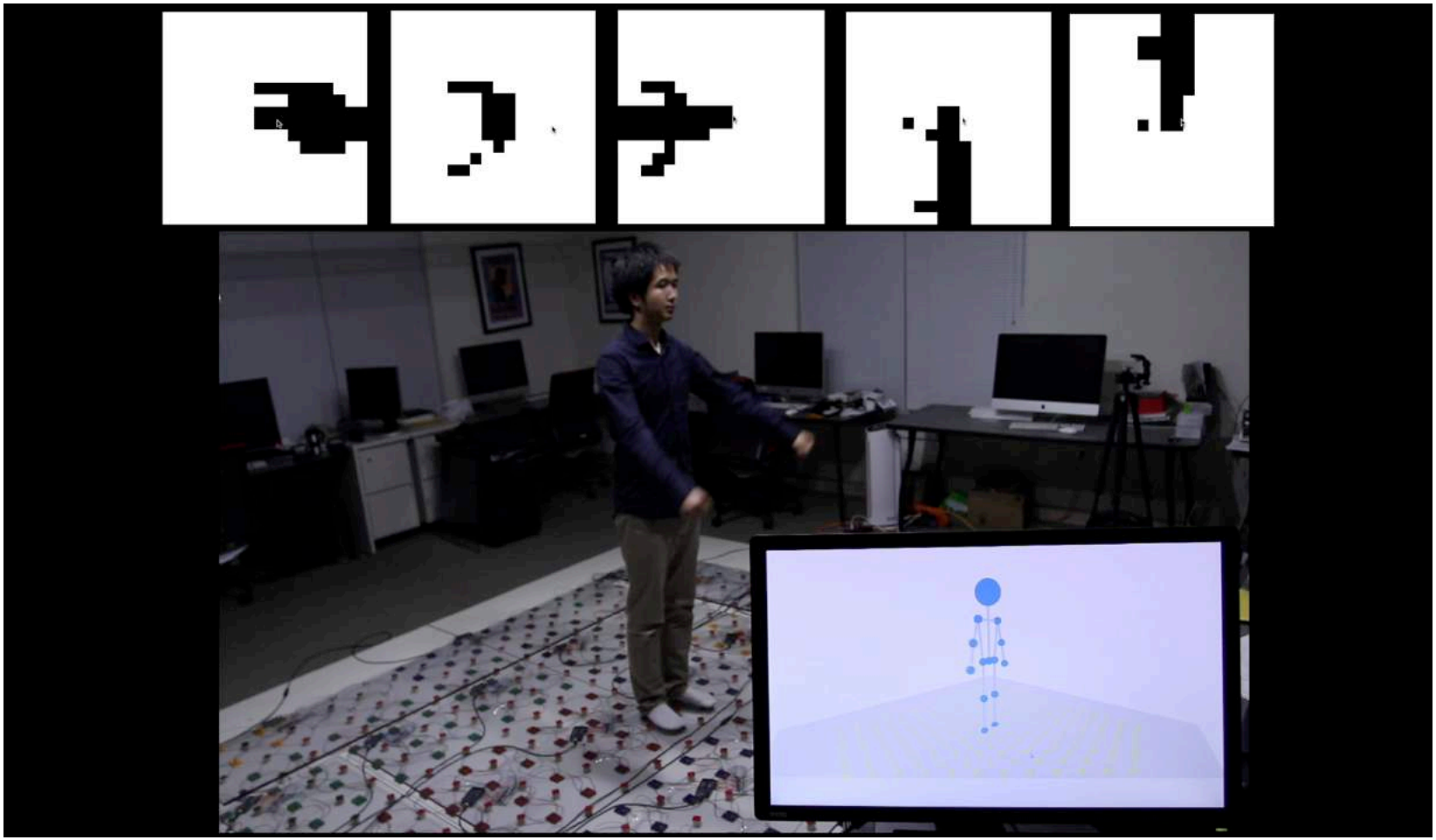


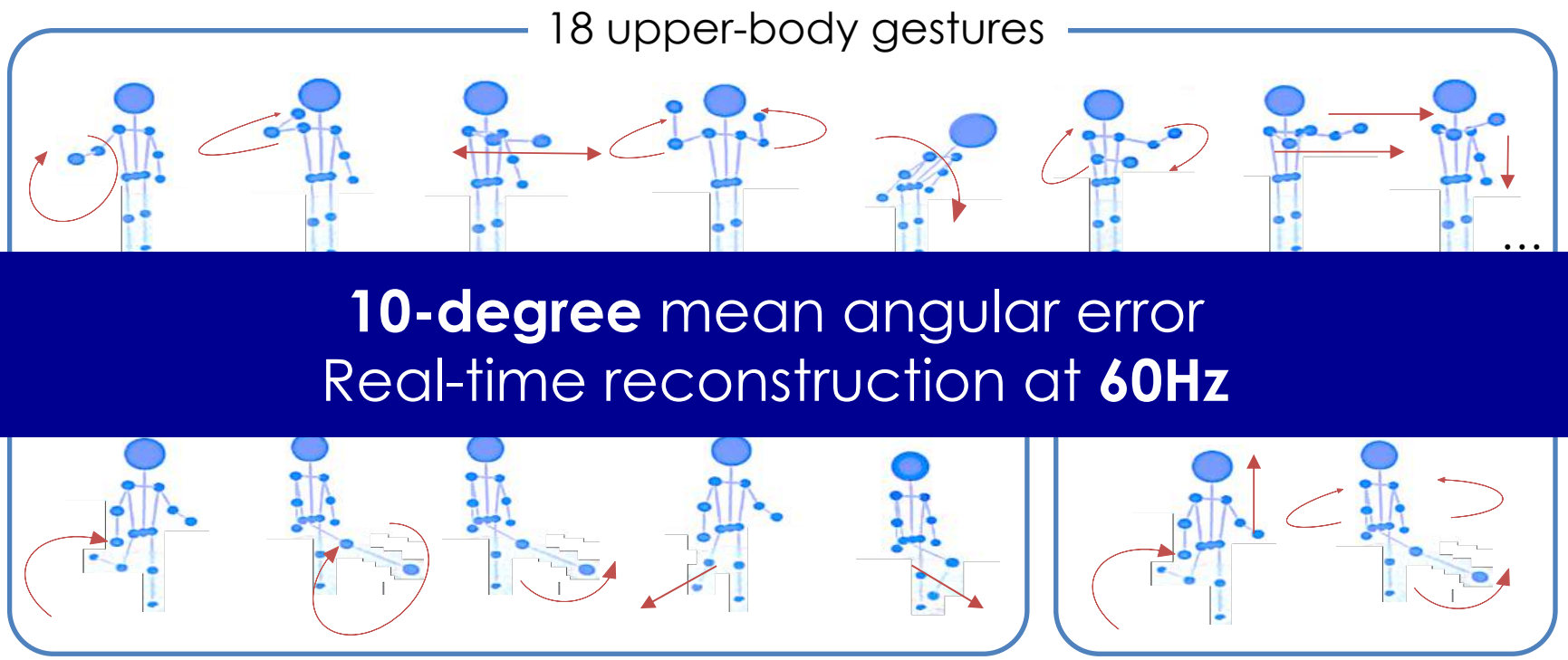
# Shadow-Based Inference



# iSense

- 7 users
  - 169 cm – 190 cm
  - 60 kg – 80 kg
- Ground truth
  - Human labelling using 3 cameras

# Key Results



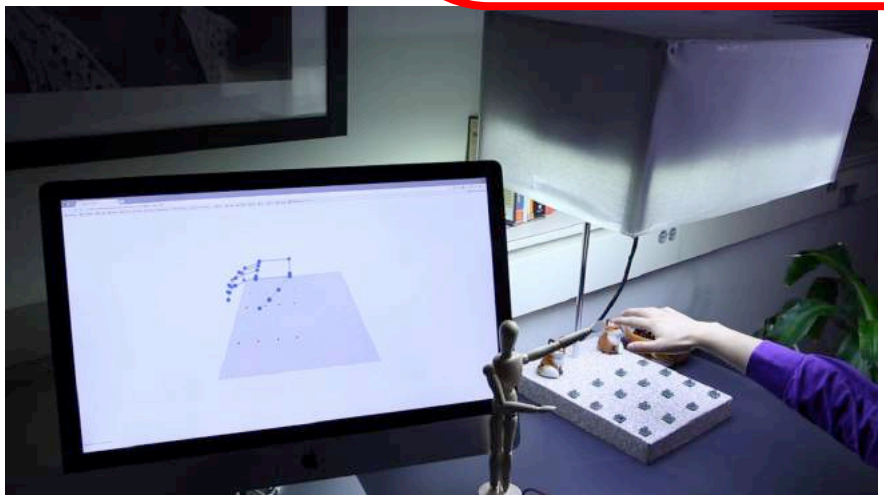

**10-degree** mean angular error
Real-time reconstruction at **60Hz**

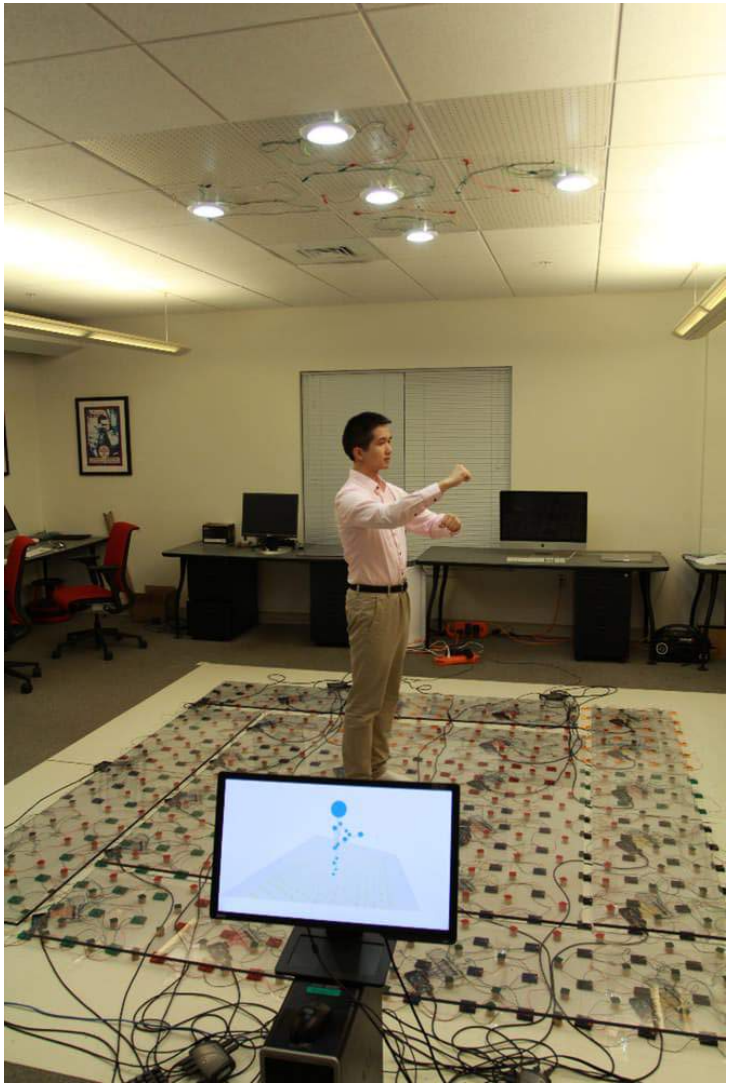
# Skeleton Pose Estimation

**LiSense**

**StarLight**

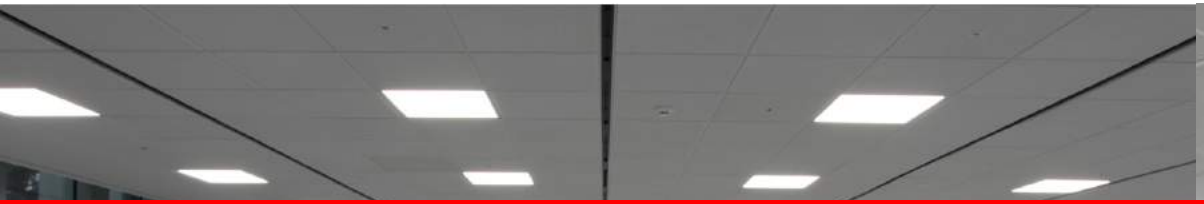
**Aili**



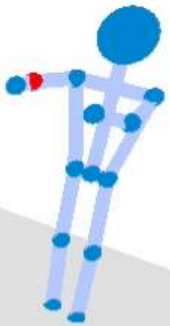


- Too many sensors...
- Static user with known orientation
- Furniture can block light too…






Exploit the large number of lights to reduce sensors!

- Right elbow

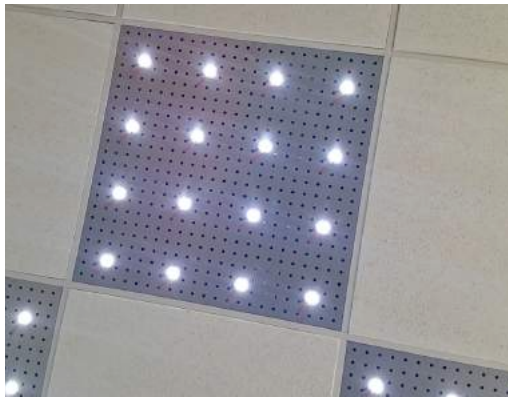
Video link: https://youtu.be/DIDxR4zdrds

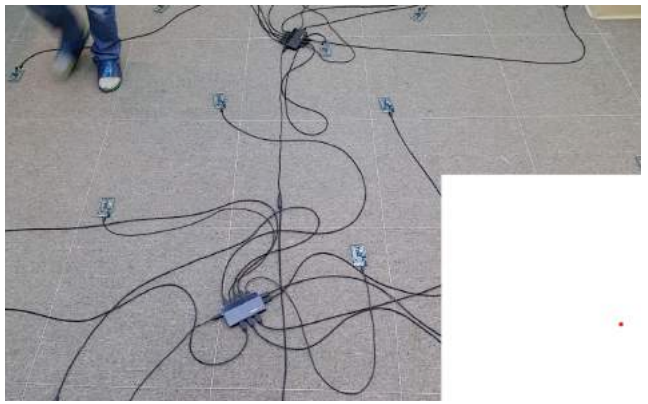
# Main Challenges

Dense LEDs

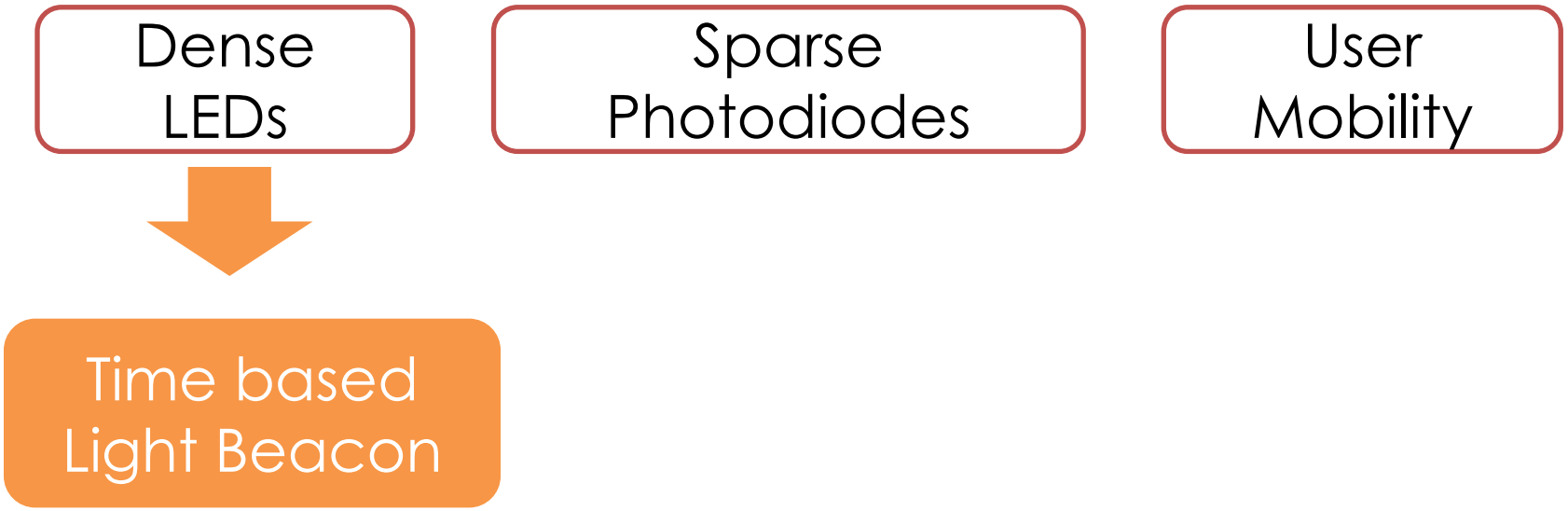
Sparse Photodiodes

User Mobility

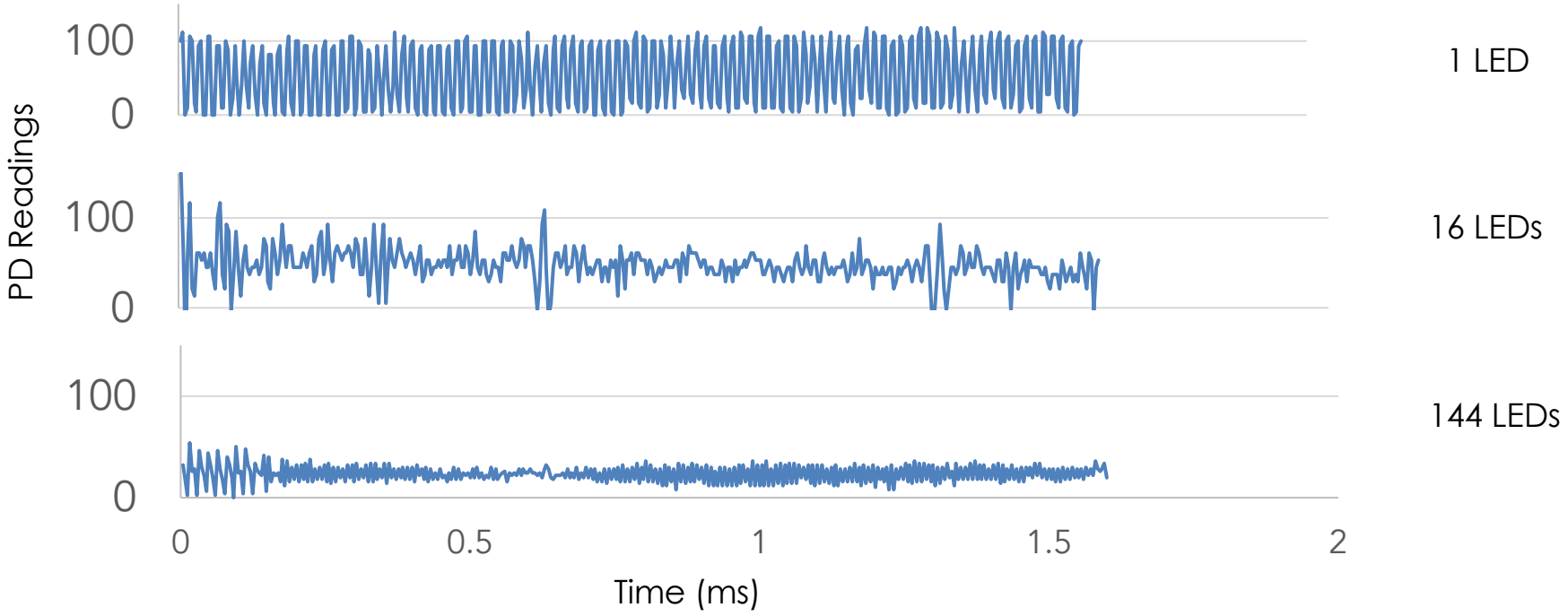




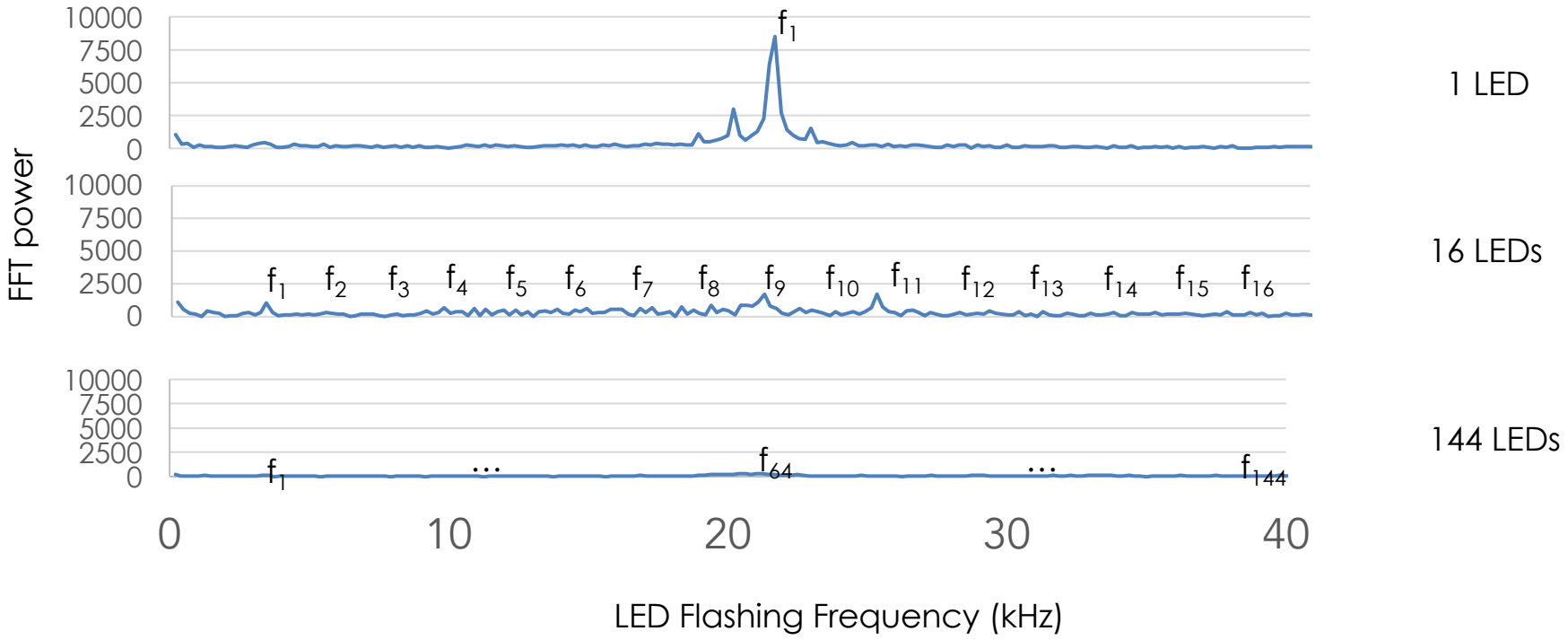
# StarLight Overview



# Impact of Dense LEDs

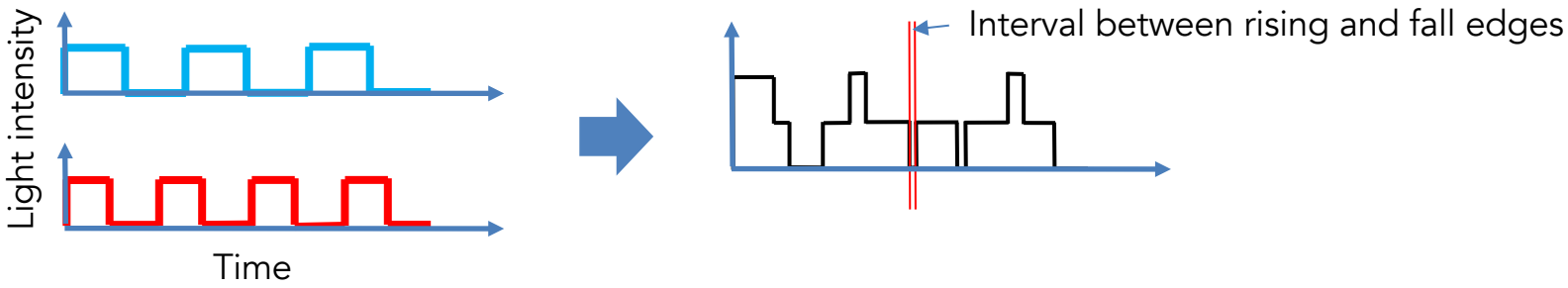


# Impact of Dense LEDs



# Why Do Dense LEDs Make it Hard?

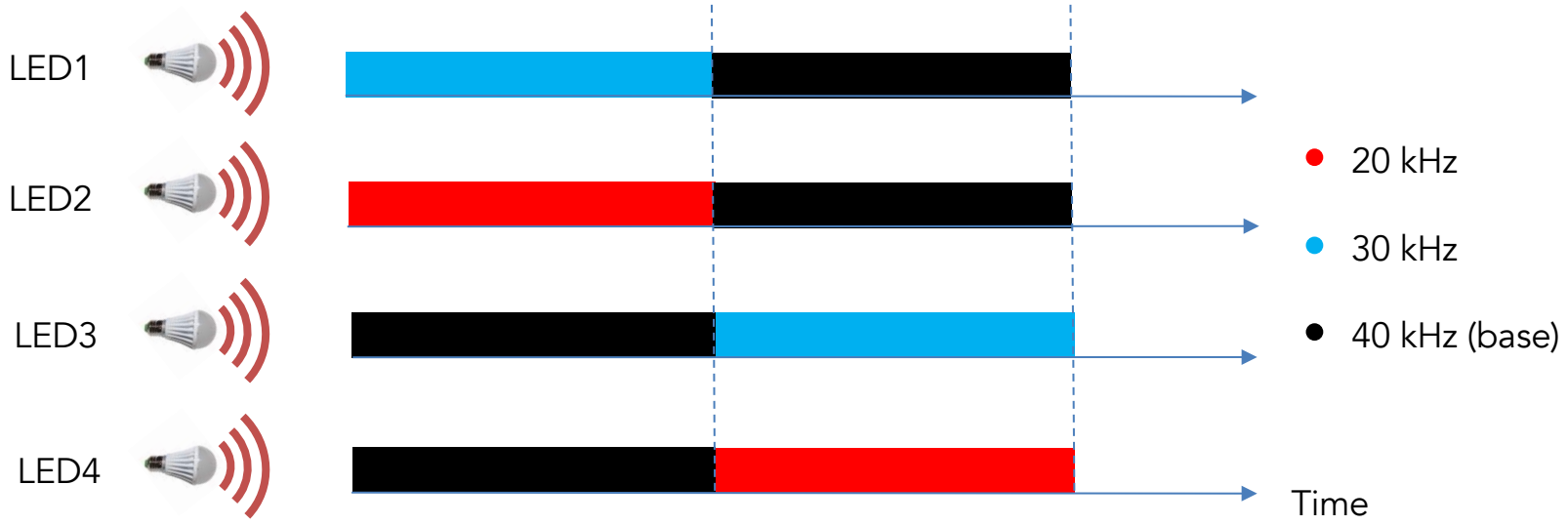
- Flashing frequency range is limited (20 -- 40 kHz)
- The more frequencies, the smaller the interval between adjacent rising and fall edges



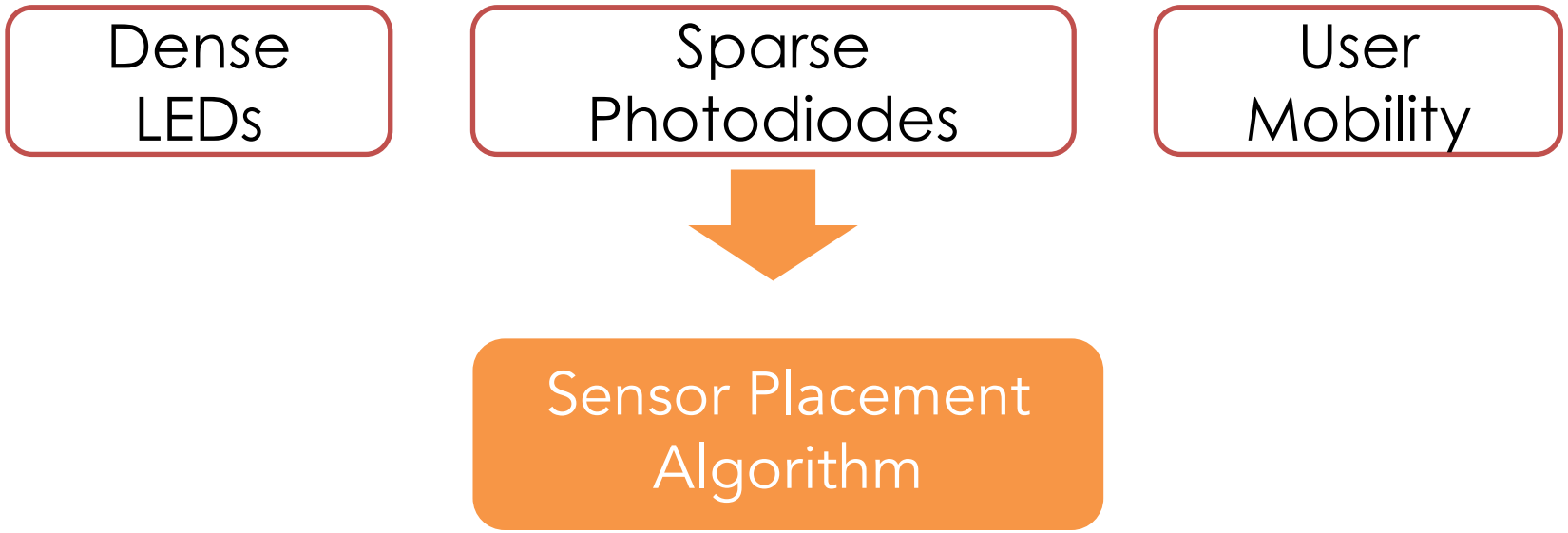

Rising and fall edges can be too close for photodiodes to respond ☹

# Time-Based Light Beacon

- Reuse light beacon frequencies over time
- Combine beacon frequency and beacon time slot to identify an LED

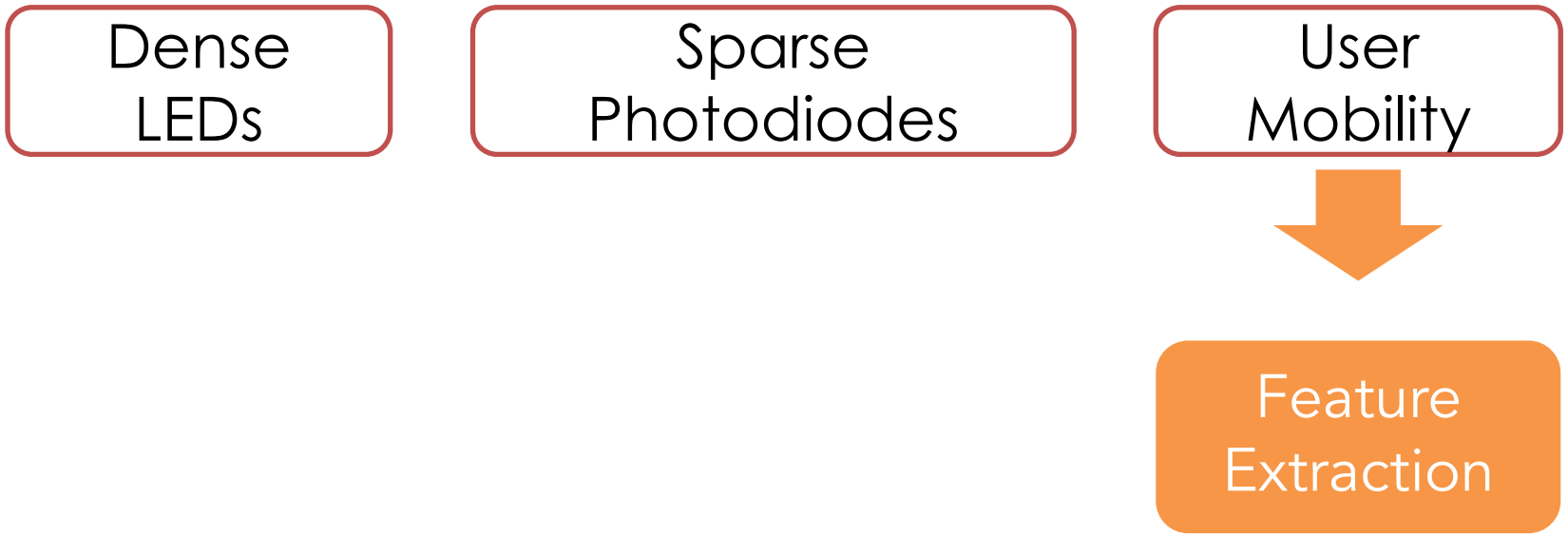


# StarLight Overview



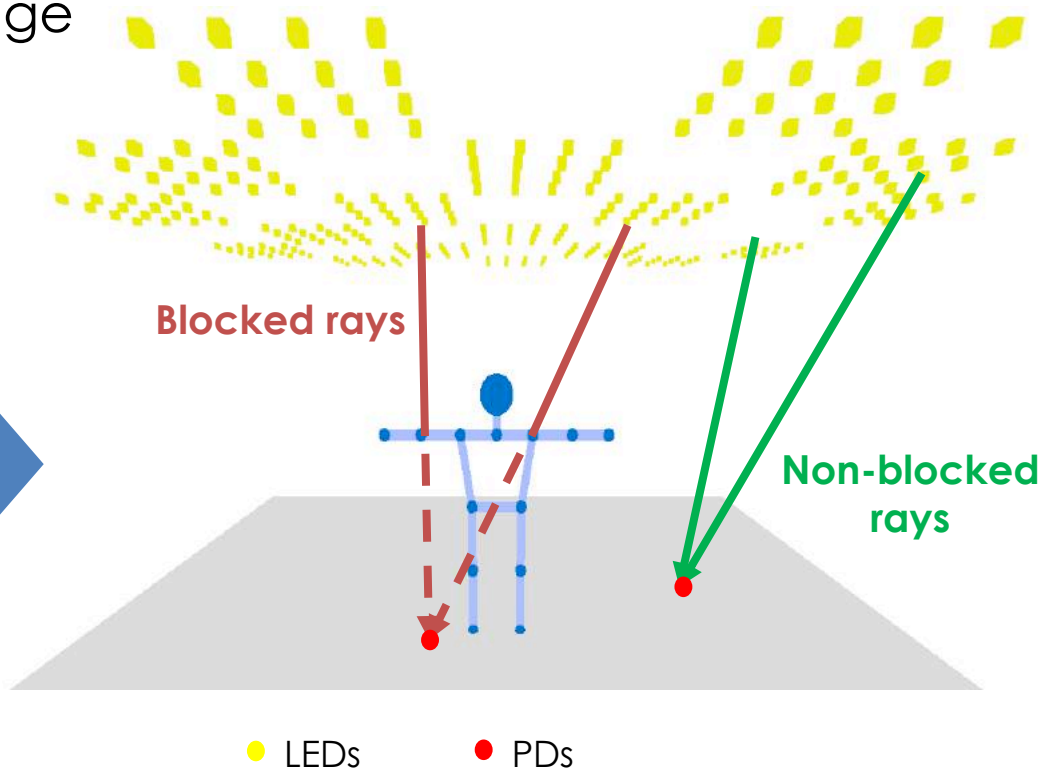

- Reduced to the maximum set coverage problem
  - Monotonic and Submodular
  - Efficient greedy solution with (1 – 1/e) approximation ratio

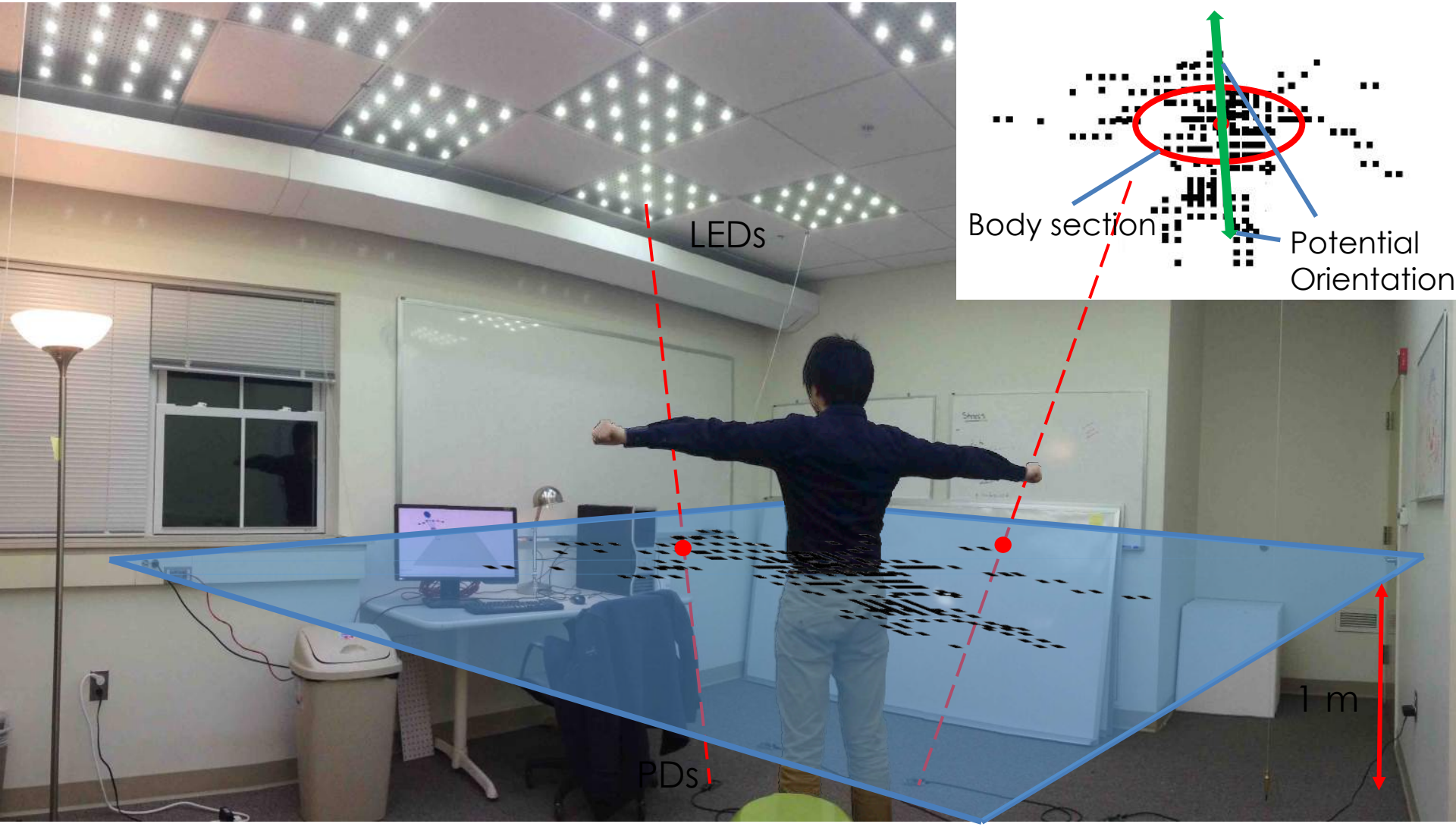
# StarLight Overview



# Tracking a Mobile User

- Search for the best-fit skeleton based on the light blockage information

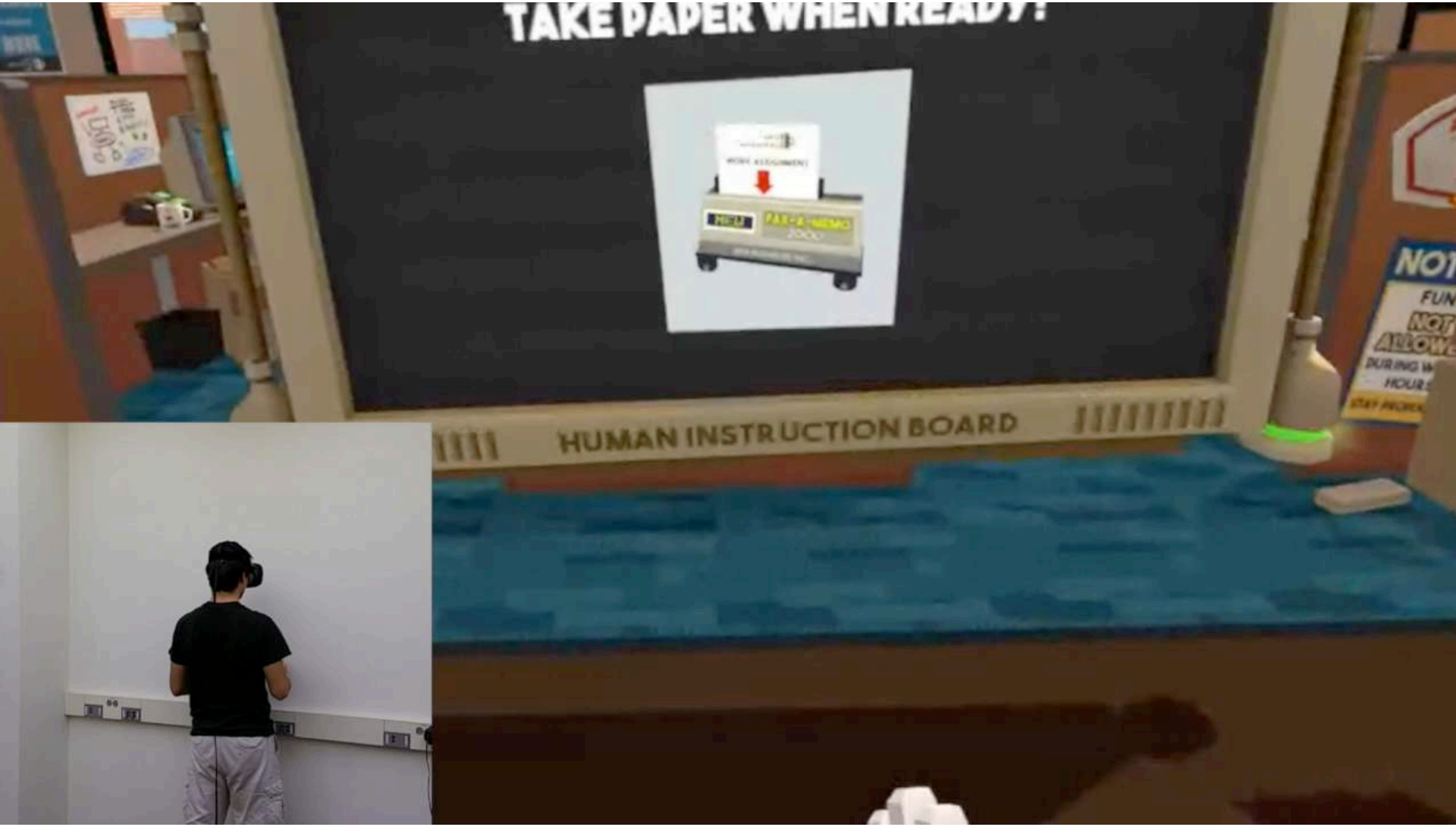



LEDs
Body section
Potential
Orientation
1 m
PDs


- Setup
  - 3.6m x 4.8m office room
  - 1 Linux Server
- x 10
  - 158 cm – 190 cm
- Ground truth
  - Kinect 2.0

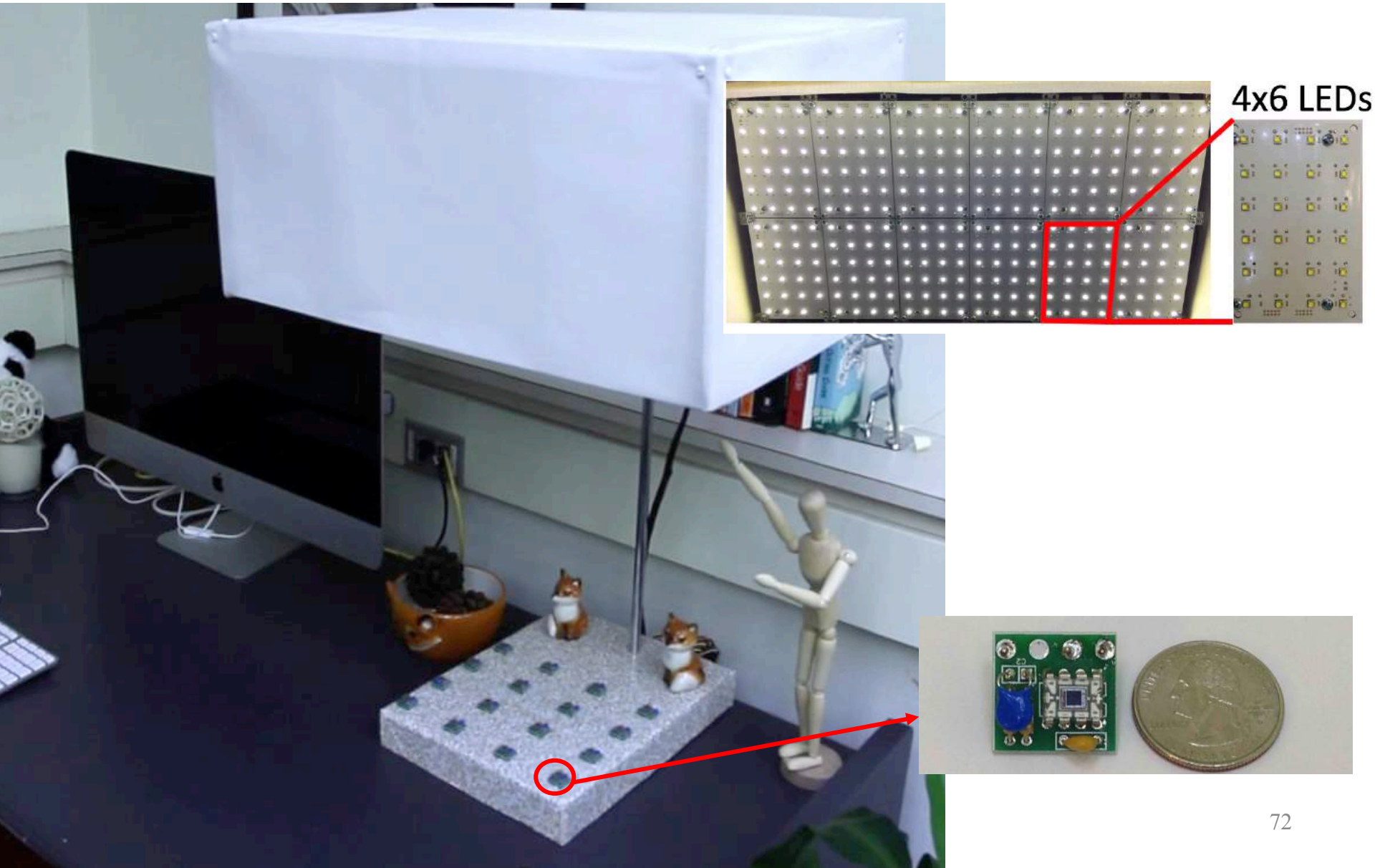
**14-degree** mean angular error
Real-time reconstruction at **40 Hz**

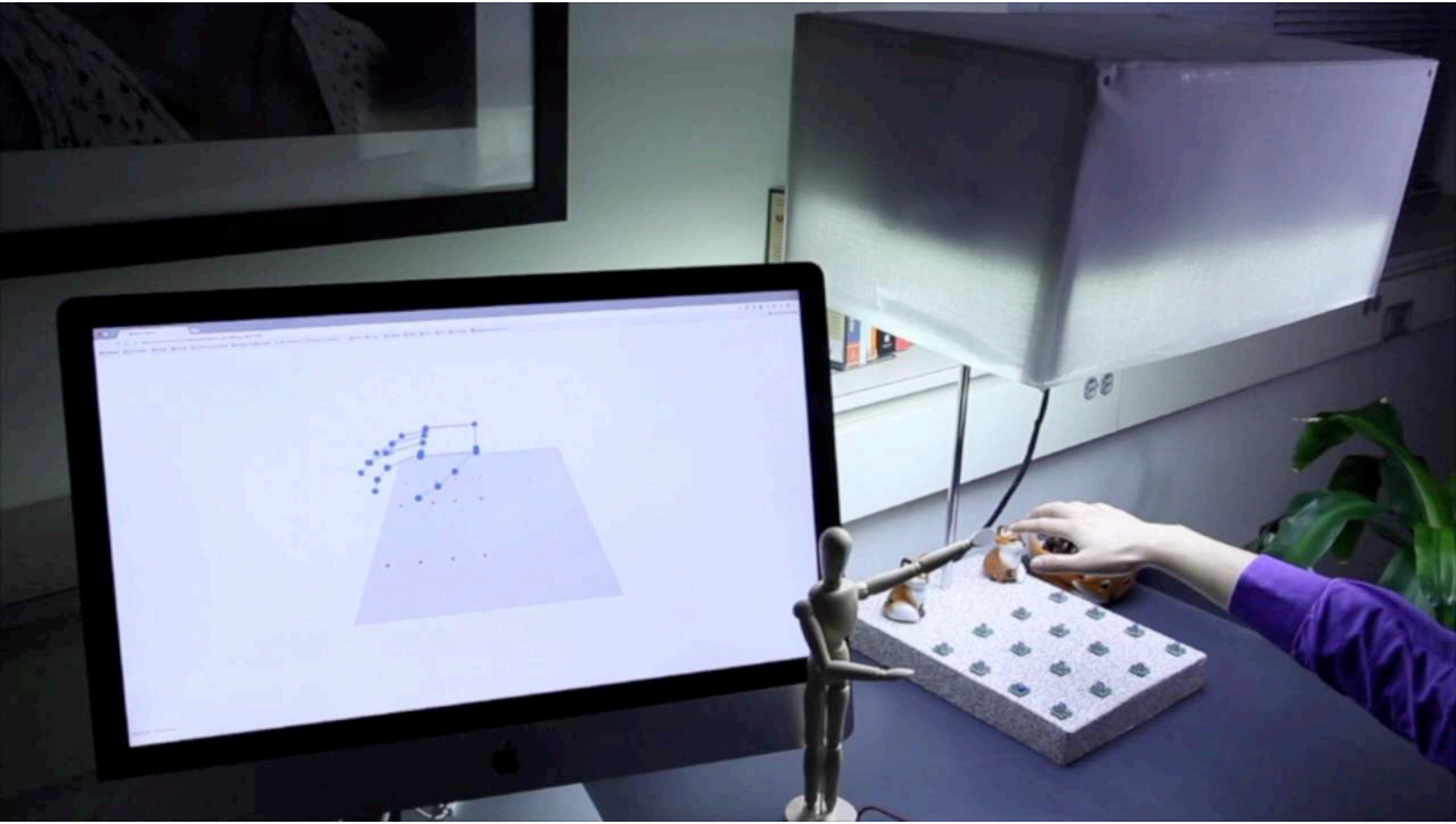
# Application: User Interaction Designs


TAKE PAPER WHEN READY!
HUMAN INSTRUCTION BOARD

# Application: Behavior Monitoring

# Reconstructing Hand Poses



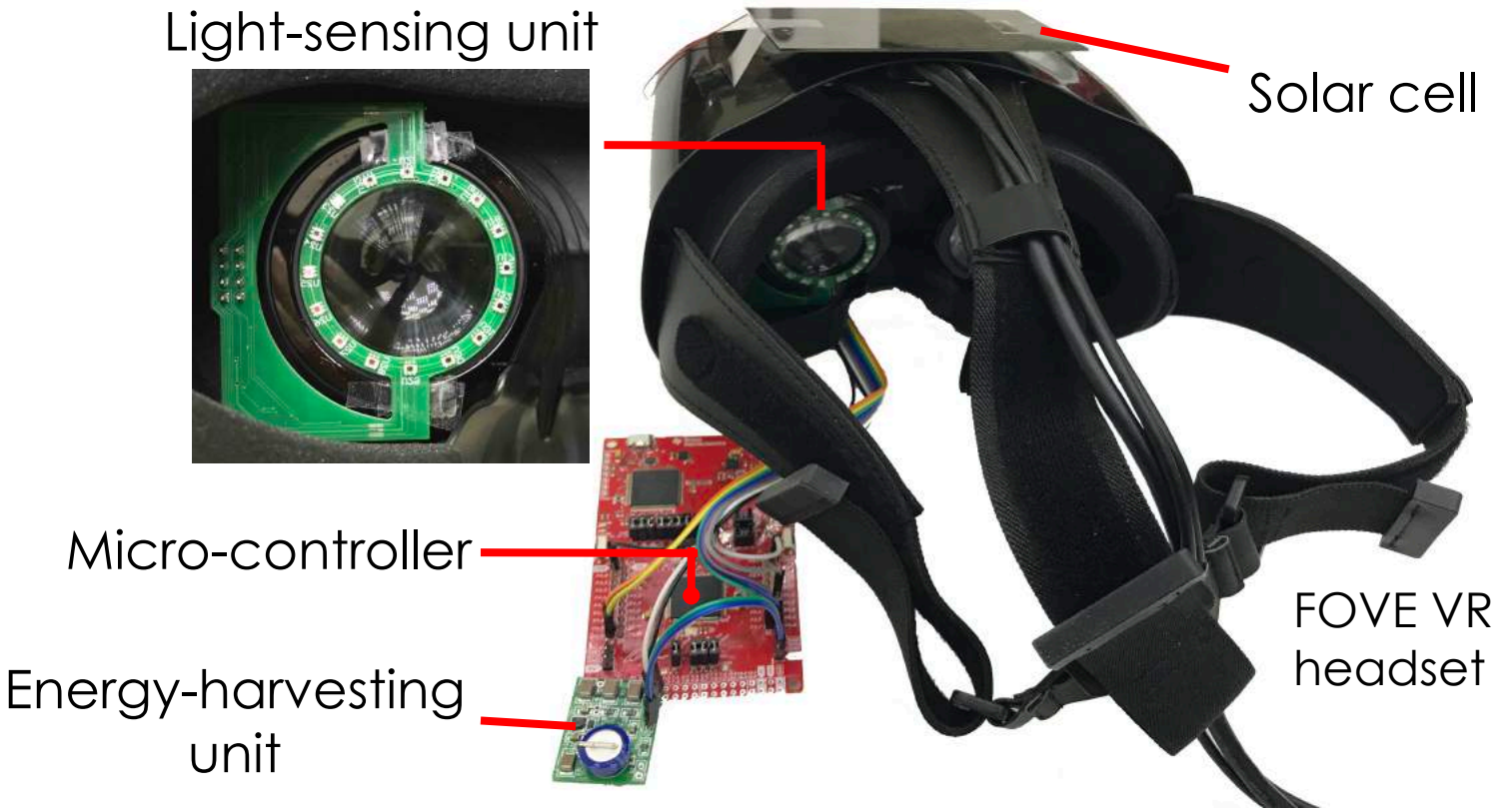


Video link: https://youtu.be/Fl1vVc3UGLA

# Open Research Challenges

- Lower deployment overhead, low-power sensing
- Deployment in a reasonable scale
- Fusion with other sensing modality
- Innovative, interdisciplinary applications
  - HCI, robotics, graphics/vision, security/privacy, health

# Reusing VR Screen Light for Gaze Tracking



# Communication and Sensing Using Light

*http://dartnets.cs.dartmouth.edu/*

dartnets