

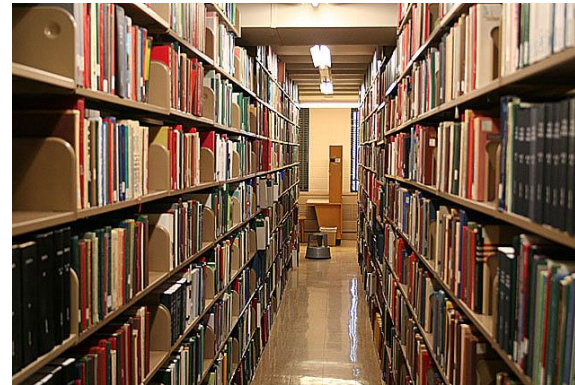
Epsilon: A Visible Light Based Positioning System

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Motivation: the need of higher precision

- WiFi-based indoor positioning and tracking:
 - Point positioning: several meters
 - Tracking: few meters
- Scenarios needs higher accuracy:
 - Precise navigation to the object
 - Books on bookshelves
 - Goods on stacks in grocery store
 - Physical analytics
 - Gestured-based interaction
- Human desire never ends...

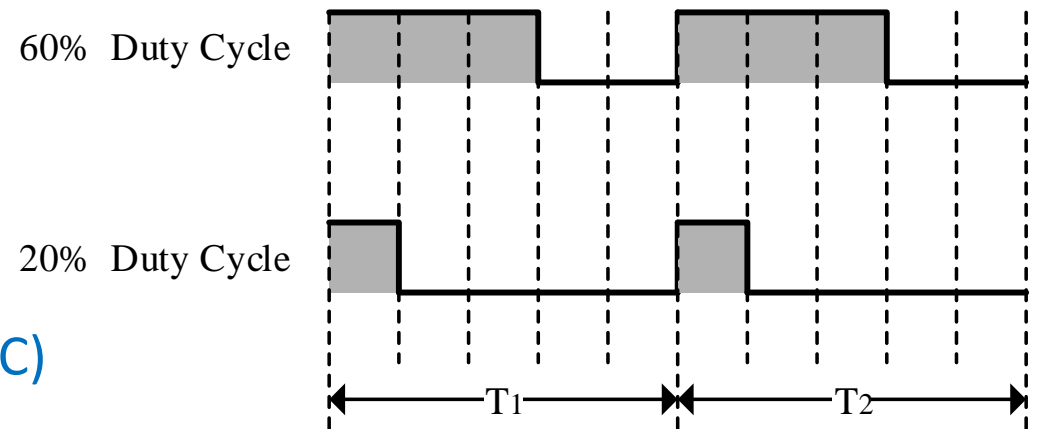


Exploring the visible light medium – LEDs

- Increasingly widespread of LED lighting
 - High lighting efficiency (2x, compared with CFL)
 - Long lifespan (6x, 60,000 hours)
 - Environment friendly (mercury free)
 - Long-term cost savings

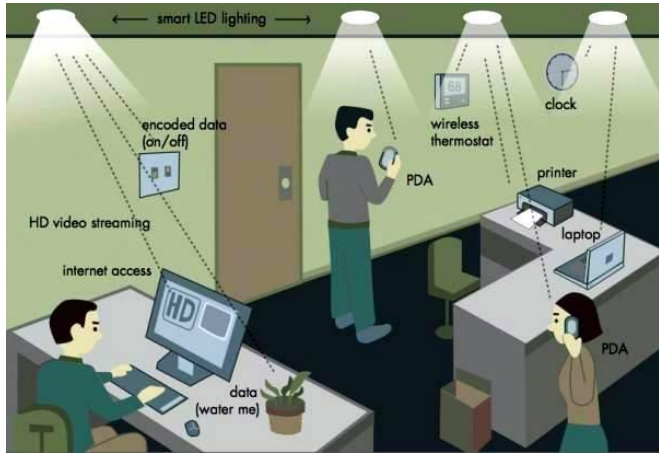
- Instantaneous on/off
 - 4 microseconds transition time
 - PWM for dimming purpose

Suitable for visible light communication (VLC)
→ Dual-paradigm (illumination + comm.)

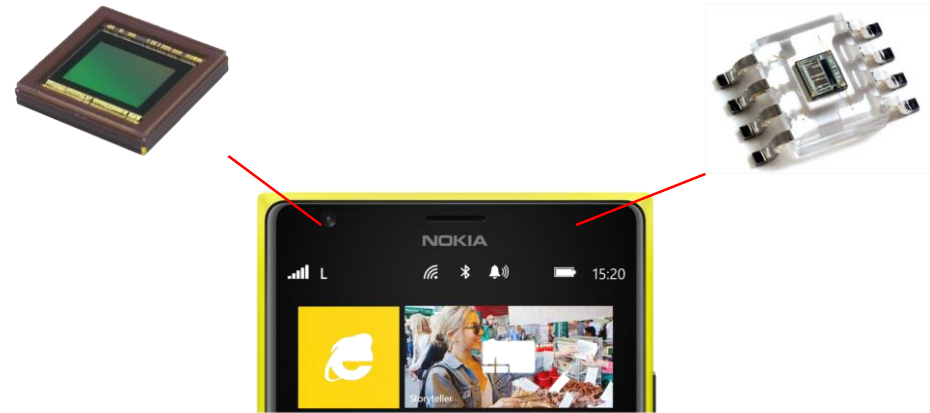


Advantages of exploring visible light

Visible Lights (infrastructure)



Light/Image Sensor (on device)



- High density: order of magnitude denser than WiFi.
- Visible: easy to get human in loop.

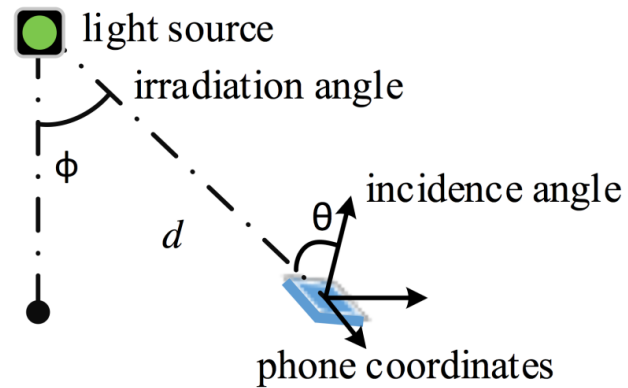
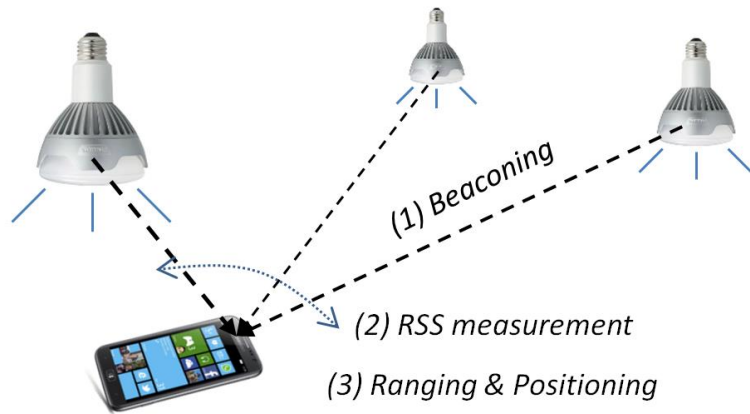
Achieve high accuracy by leveraging the *existing* infrastructure!

Basic concept of Epsilon

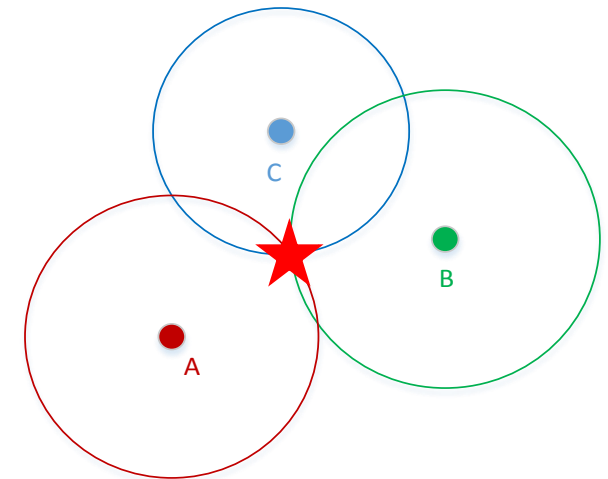
Sensing

Ranging

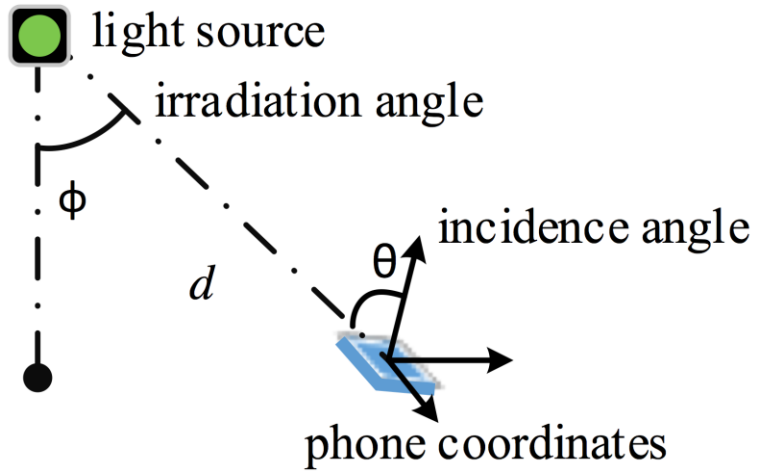
Trilateration



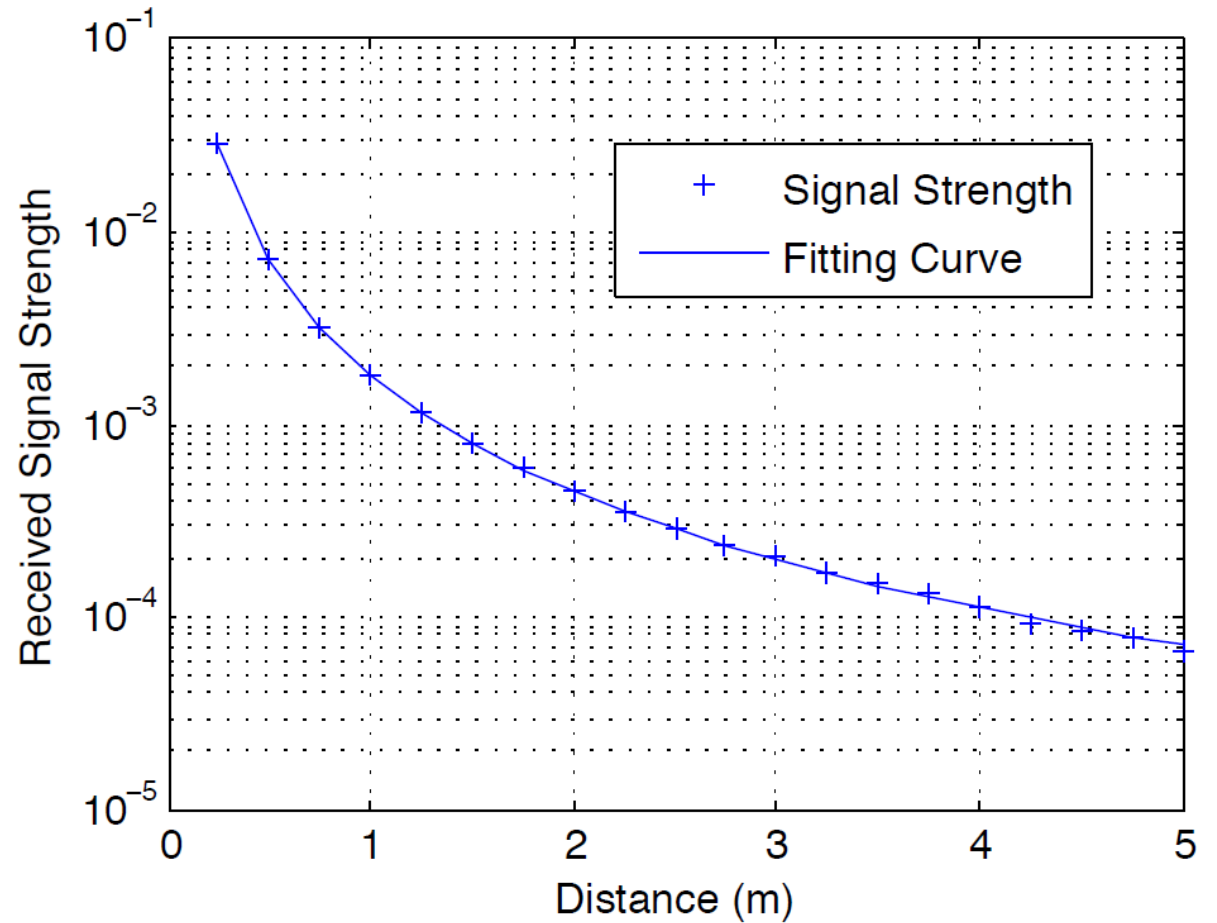
Optical channel model



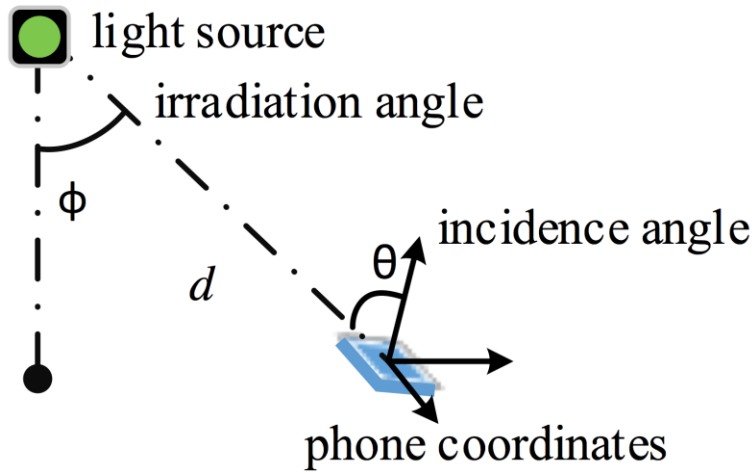
The optical channel model



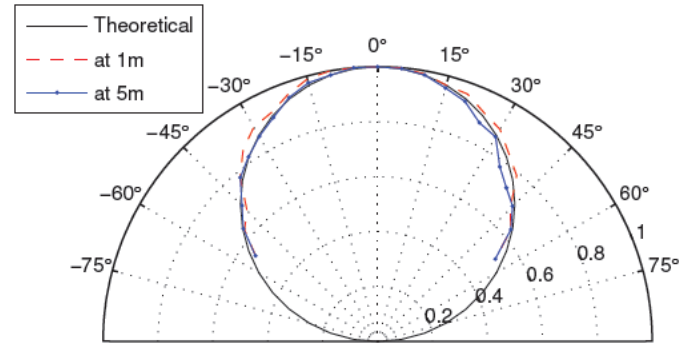
$$P_r = P_t \cdot G_r \cdot \frac{\cos \theta \cdot \cos \phi}{d^2}$$



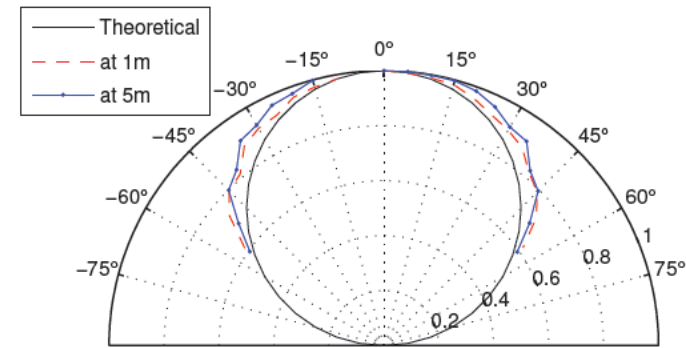
The optical channel model



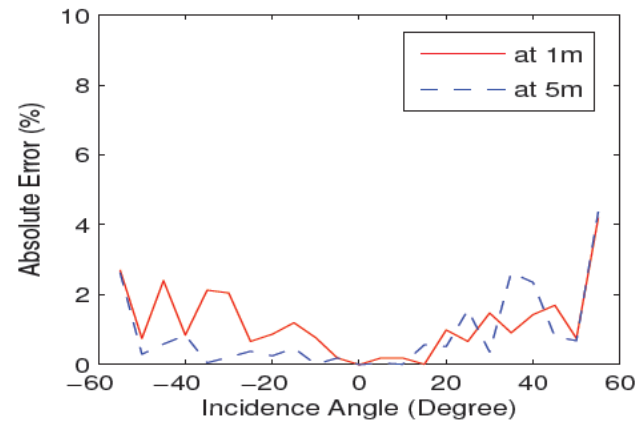
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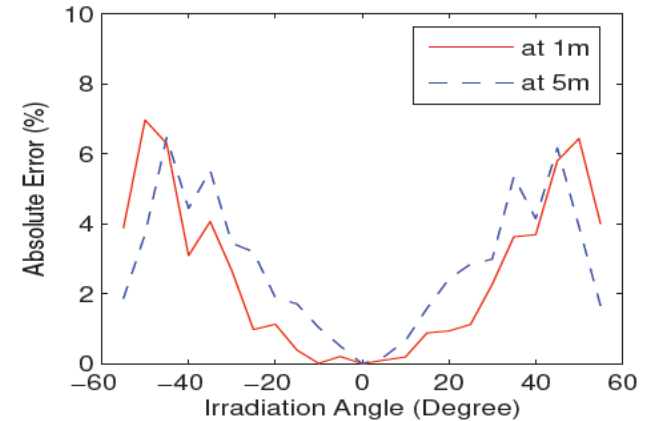
(a) Channel response of θ



(b) Channel response of ϕ

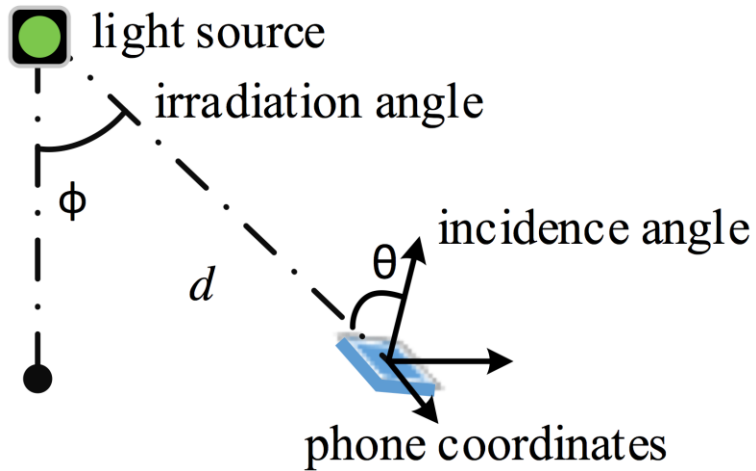


(c) Relative error of θ



(d) Relative error of ϕ

The optical channel model



- Emission power spreads over the baseband and all harmonics

$$f(t) = \frac{\tau}{T} + \sum_{n=1}^{\infty} \frac{2}{n\pi} \sin\left(\frac{\pi n \tau}{T}\right) \cos\left(\frac{2\pi n}{T}t\right)$$

- For localization, the baseband energy suffices.

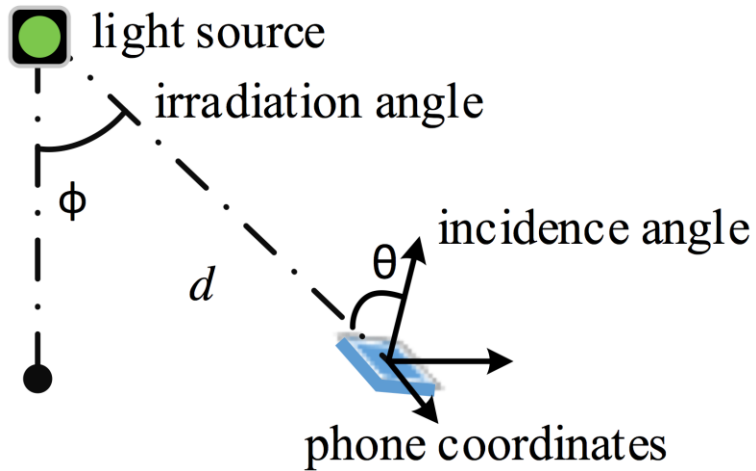
$$P_t \propto \frac{2}{\pi} \sin(\pi\tau/T)$$

$$P_r = P_t \cdot G_r \cdot \frac{\cos \theta \cdot \cos \phi}{d^2}$$

- Interestingly, a function of duty cycle $\alpha = \tau/T$

$$P_r = C \cdot \sin\left(\frac{\tau}{T}\pi\right) \cdot \frac{\cos \theta \cdot \cos \phi}{d^2}$$

The optical channel model



$$P_r = C \cdot \sin(\alpha\pi) \cdot \frac{\cos \theta \cdot \cos \phi}{d^2}$$

C Normalized Constant

α Duty cycle

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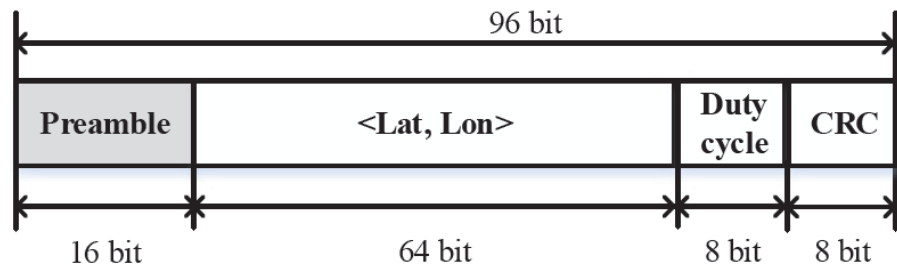
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Design: practical considerations

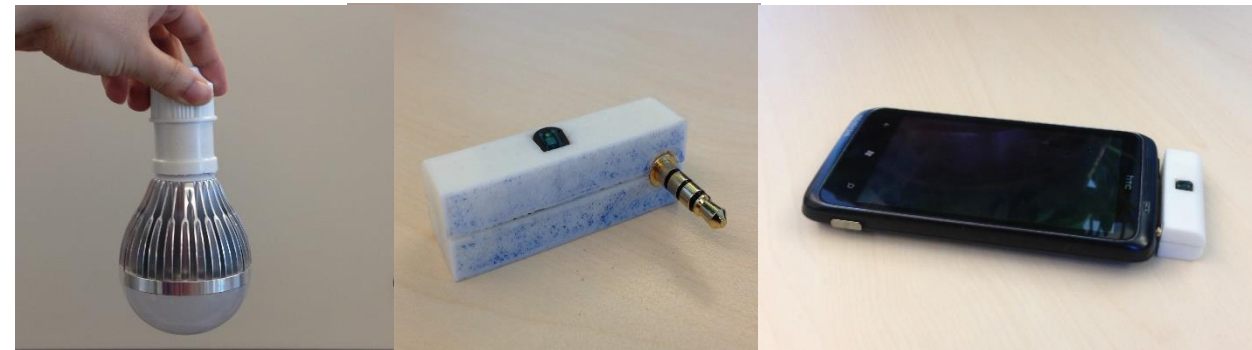
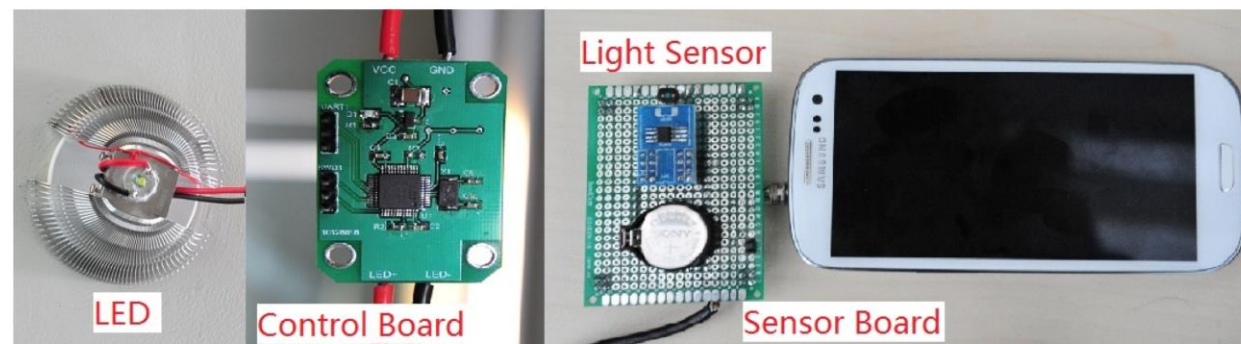
- Choosing the right method for communication
 - LED lights support up to 100kHz
 - Must be higher than 200Hz to avoid flicker
 - Stay away from 50/60Hz interference
 - Avoid self-interference by harmonics
- Limited sampling frequency of light sensors on commodity phones
 - Capped by the driver
 - Up to few hundred Hz

Prototype

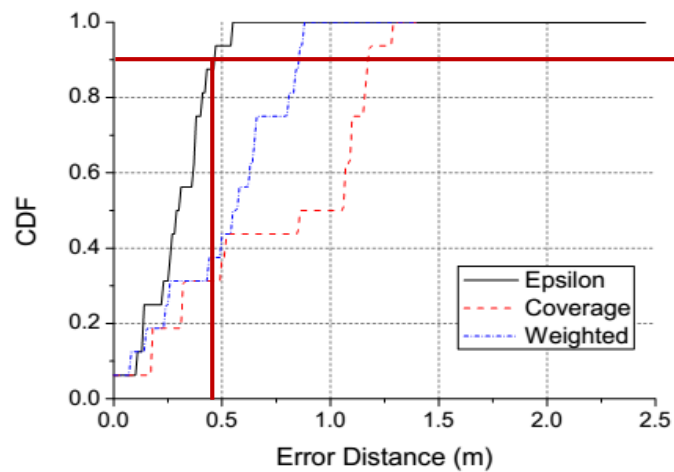
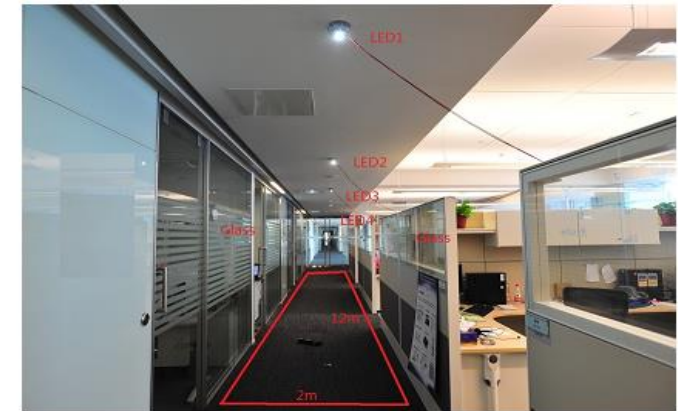
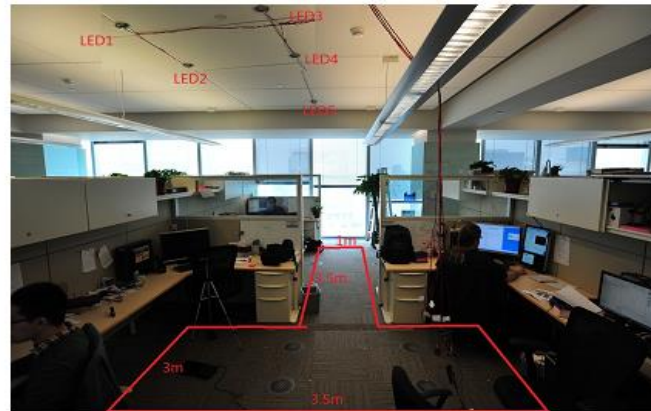
- Modify off-the-shelf LED bulb
 - Add a control board implementing BFSK beacons



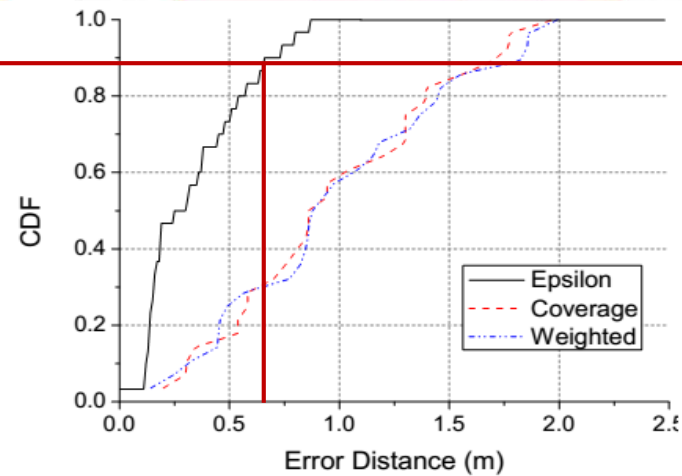
- Phone + Light sensor board
 - Add a dedicated light sensor board to the audio jack
 - Optical spectrum: 10KHz ~ 19 KHz
 - # of channels: 30
 - Channel bandwidth: 300 Hz



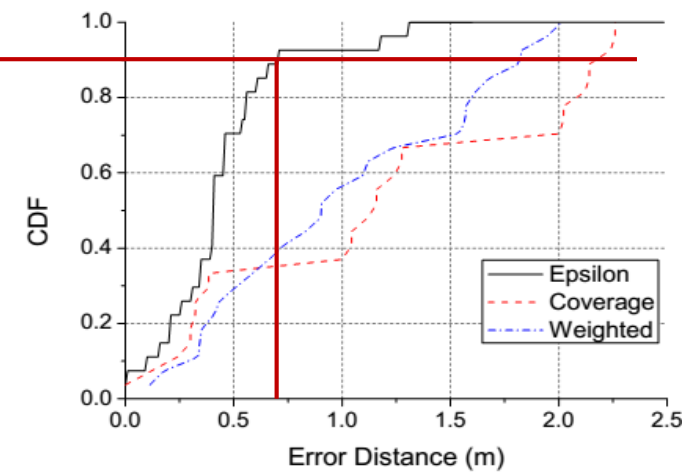
Evaluation



(a) Conference Room



(b) Cubicle Area



(c) Corridor

Sub-meter accuracy across various environments

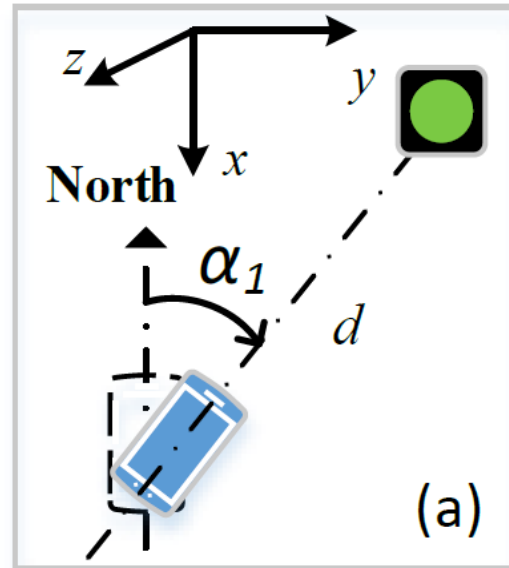
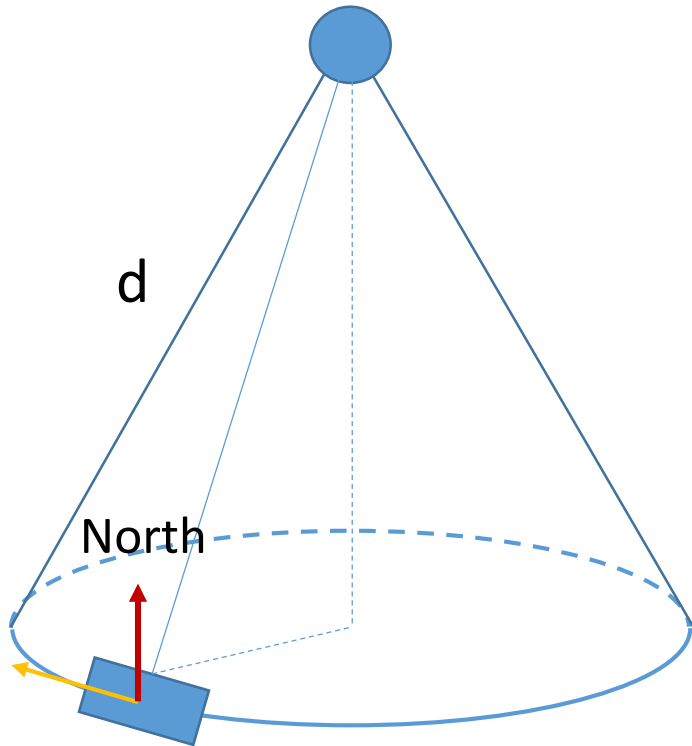
Evaluation: comparison against WiFi-based

Maximum error at 90 percentile of different methods:

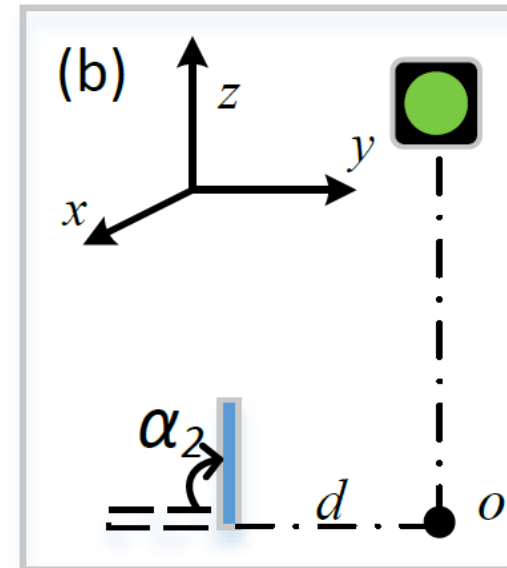
Name	EZ MobiCom'10	Radar INFOCOM'00	Horus MobiSys'05	PinPoint NSDI'13	ArrayTrack NSDI'13	Pharos This paper
Accuracy	2~7m	3~5m	~1m	2~3m	~0.9m	0.4~0.7m
Method	Model	Fingerprint	Fingerprint	Angle	Angle	Model
Database	Yes	Yes	Yes	No	No	No
Overhead	Minimum	Wardriving	Wardriving	Dense AP	16 Antennas	LED Light

What if insufficient LEDs?

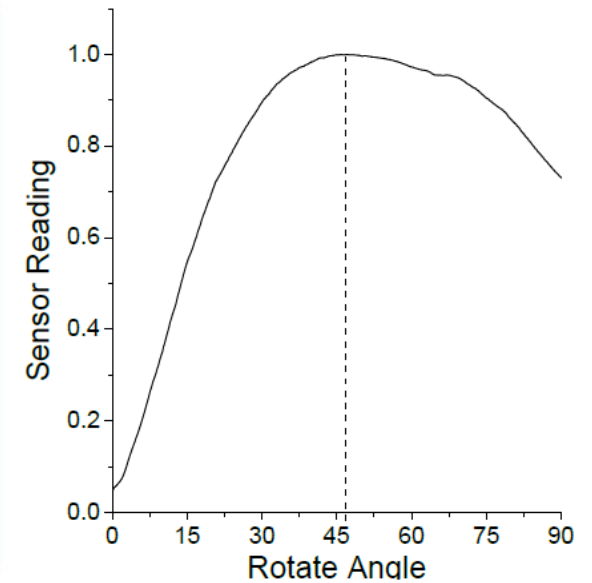
Human in loop, leverage the visibility of the bulb.



Orienting the device



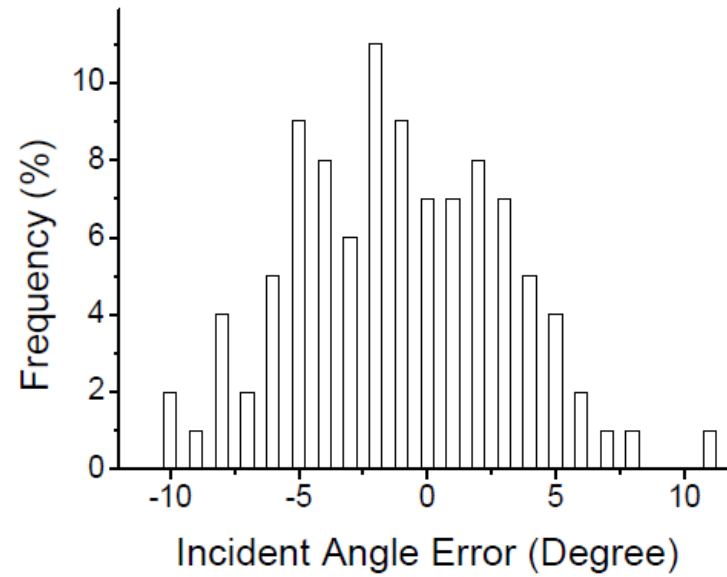
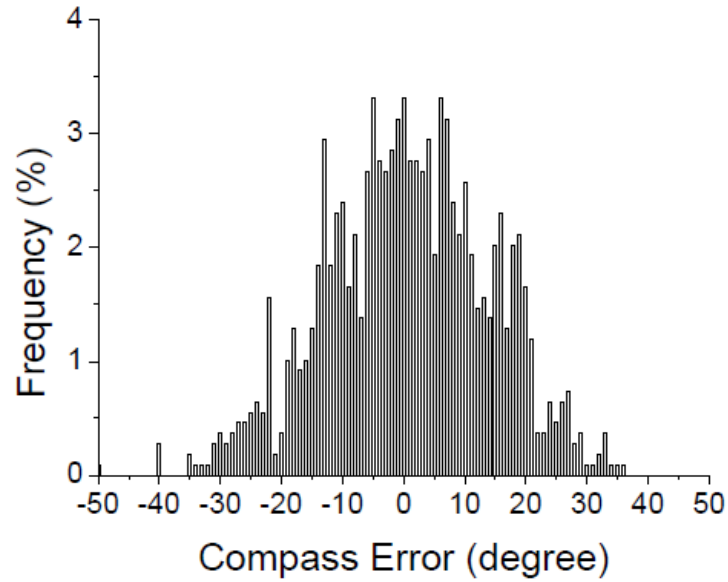
Rotate the device



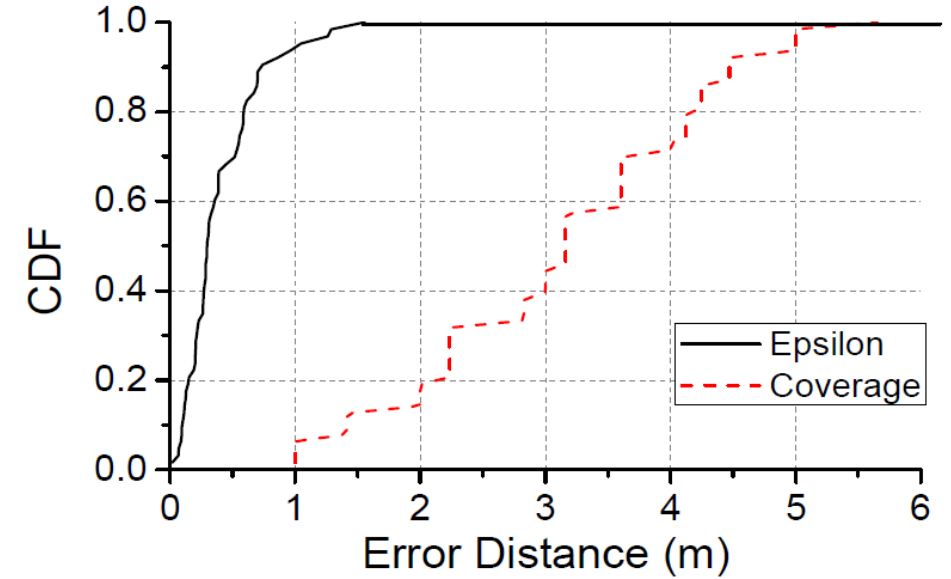
Finding the tipping point

Evaluation with a single LED

Sensing error



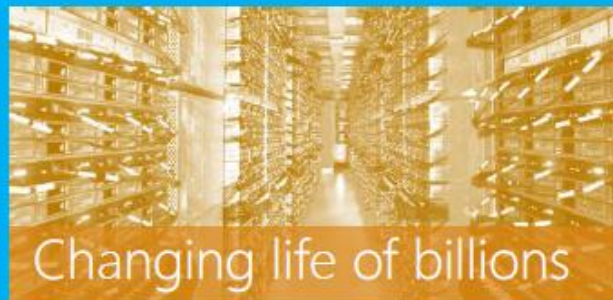
Position accuracy



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