Using Smartphones as Continuous Receivers in a Visible Light Communication System

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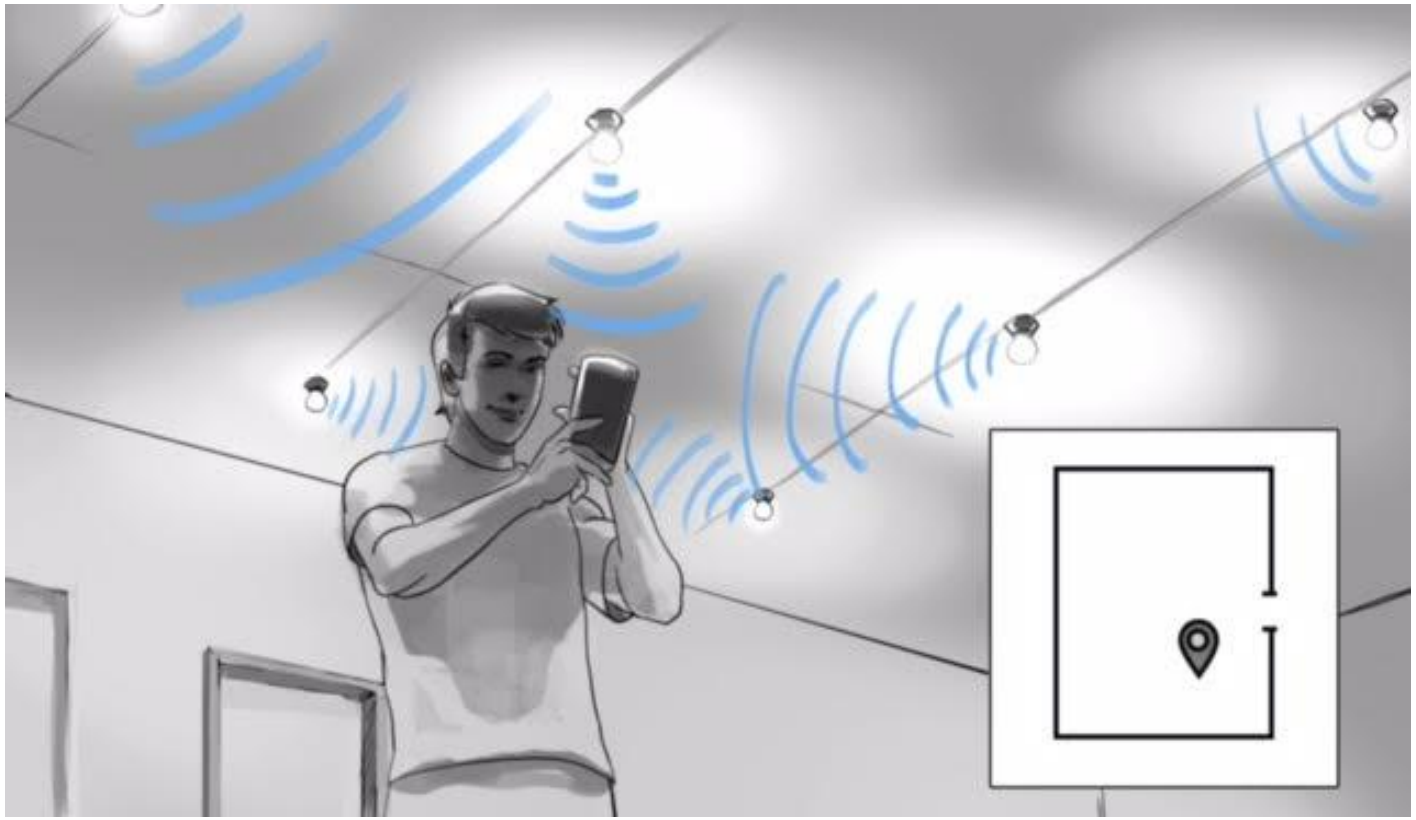
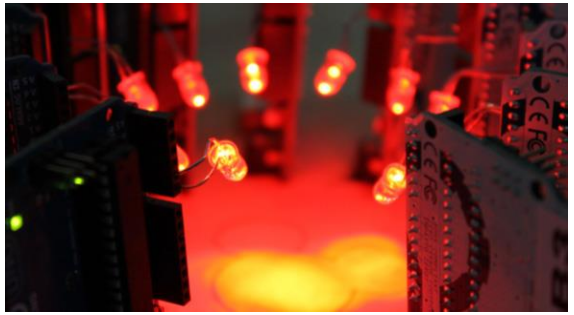
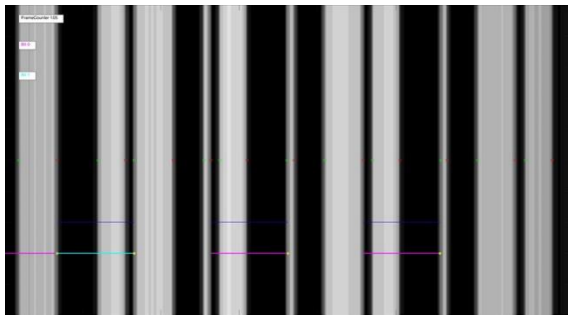
Smartphone as a Light Receiver



- No light sensor
- Ambient light sensor cannot be directly accessed and/or be sampled fast enough
- Additional peripheral is impractical
- Camera is the only option left
  - Sampling rates up to 240 Hz (FPS)
  - Exploiting the rolling shutter effect

Outline





Motivation

libvlc & EnLighting

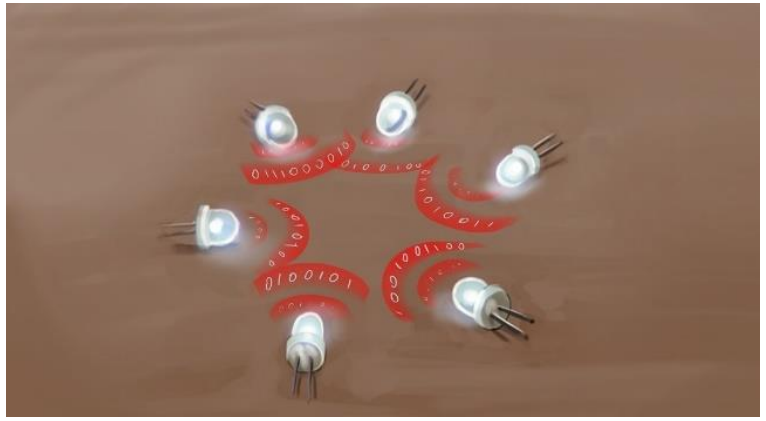
Rolling Shutter

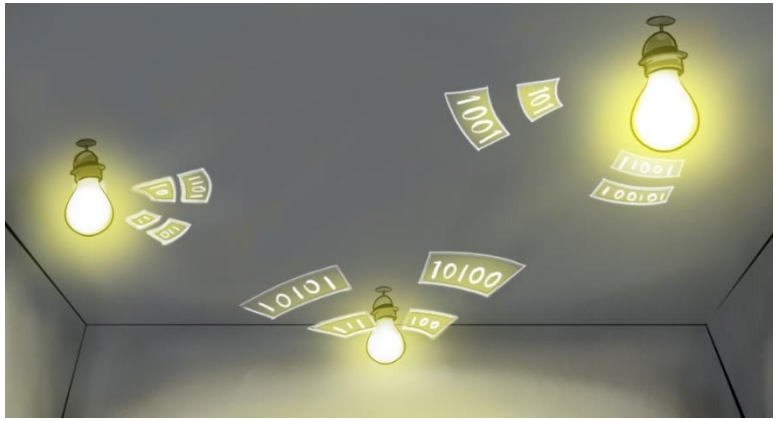
Real-Time Decoder

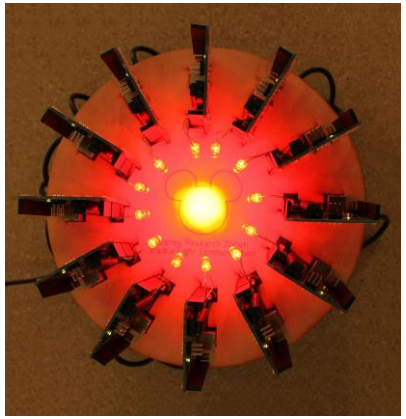
Evaluation

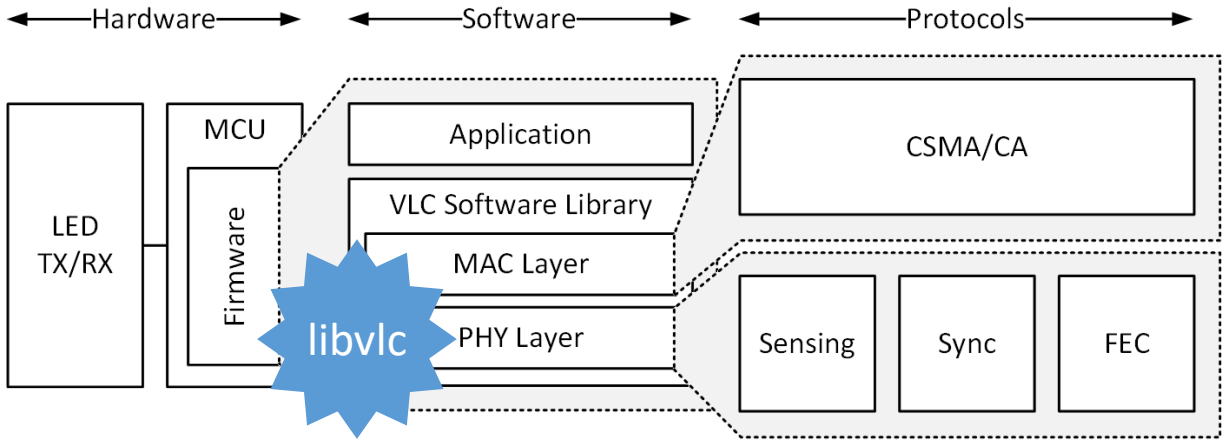
Conclusion

libvlc & EnLighting







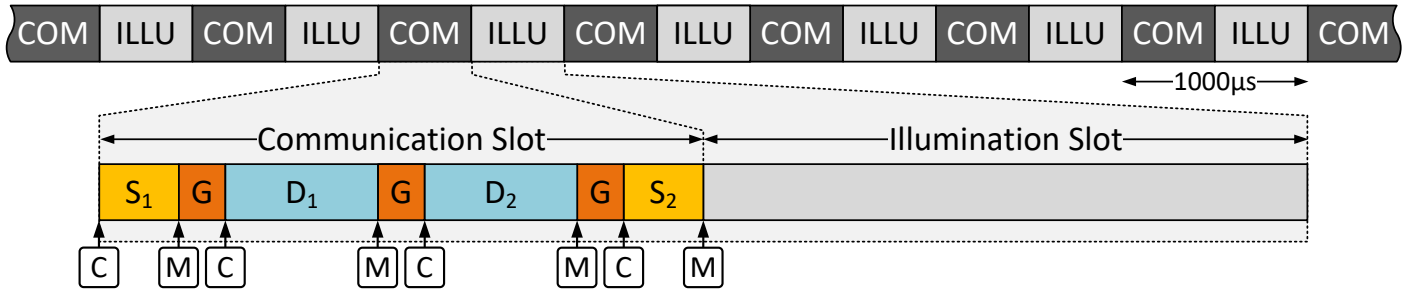


S. Schmid et al. “LED-to-LED Visible Light Communication Networks”, 2013

S. Schmid et al. “Continuous Synchronization for LED-to-LED Visible Light Communication Networks”, 2014

S. Schmid et al. “EnLighting: An Indoor Visible Light Communication System Based on Networked Light Bulbs”, 2016

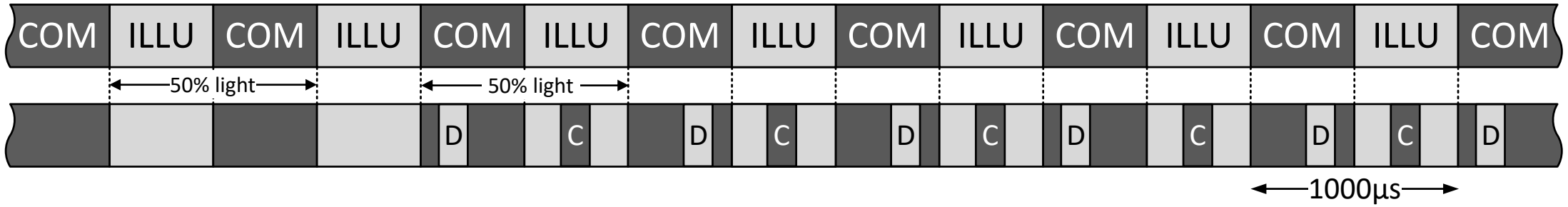
PHY Layer – Communication and Illumination



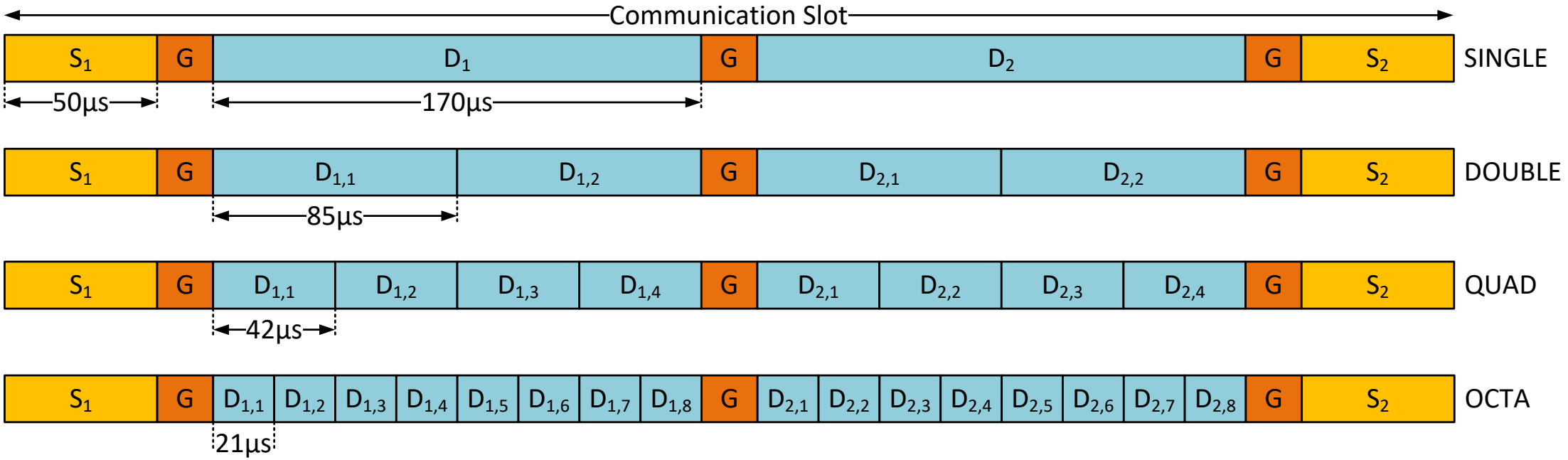
S_1, S_2: Synchronization intervals
G: Guard interval
D_1, D_2: Data intervals
C: Charge (reverse bias) LED
M: Measure remaining voltage

- Illumination (ILLU) slots and communication (COM) slots are alternating
- ILLU slots are used to provide the necessary light output for illumination
- During COM slots, there is either no light output while sensing or light output is enabled during data intervals while transmitting
- Light is sensed during the synchronization (S_1, S_2) and data (D_1, D_2) intervals

PHY Layer – Constant Light Output



PHY Layer Modes



- Shorter data intervals require more precise synchronization
- LEDs receive less light during shorter data intervals (lower signal strength)
- PHY layer mode can be selected dynamically

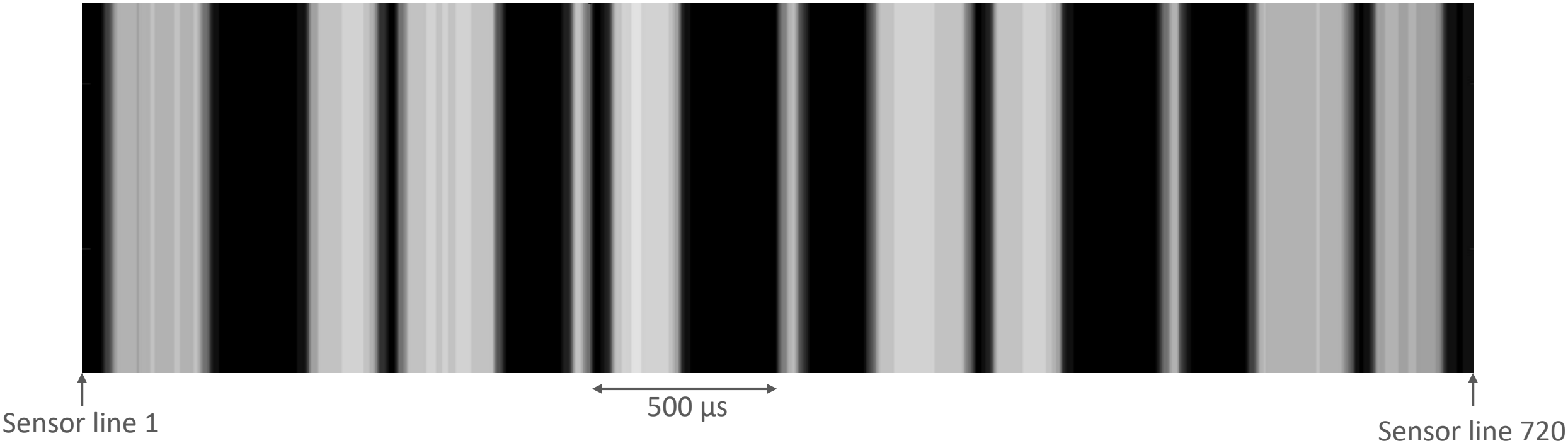
Rolling Shutter (I)

- Global shutter
- Complete image sensor is exposed at the same time
- Captures one moment in time

- Rolling shutter
- Image sensor is exposed line by line
- Captures multiple moments in time

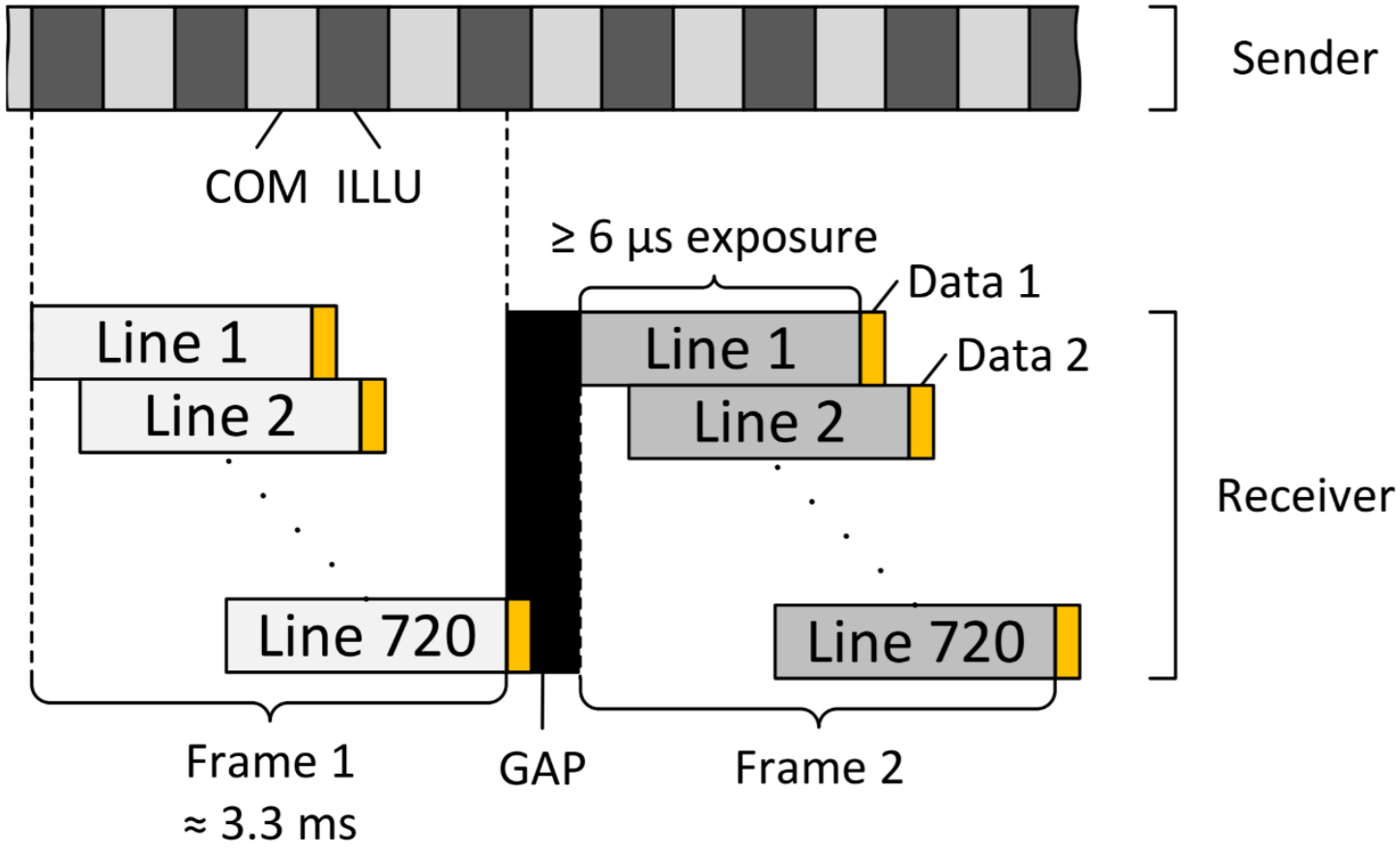
[Image Source: Point Grey Research Inc.]

Rolling Shutter (II) – Recorded Frame



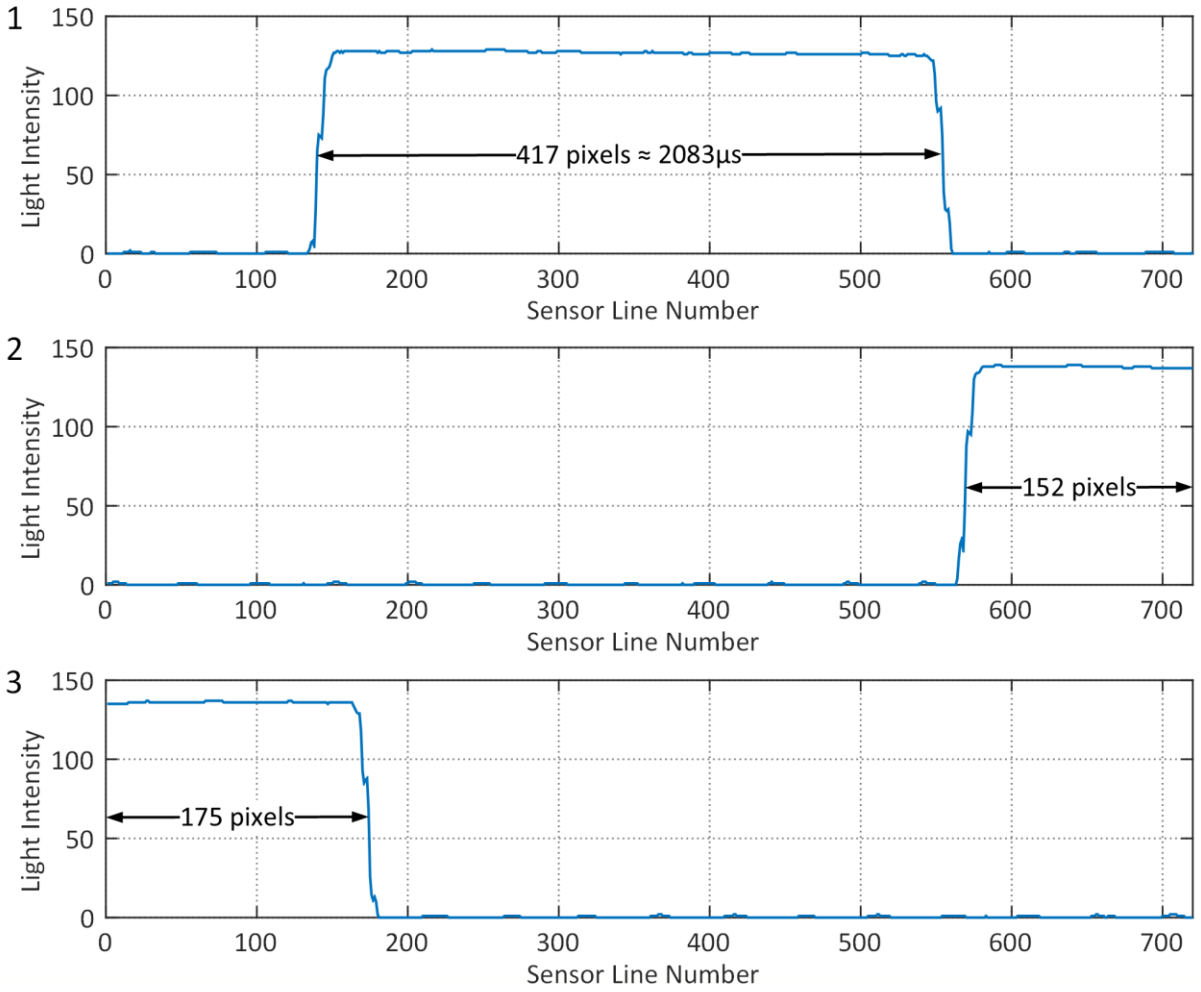
Rolling shutter extends the camera’s sampling rate (FPS)

Intra-Frame Gap



- Gap between two consecutive frames
- No light can be received
- Gap duration depends on camera and camera mode
- Higher frame rates reduce gap width
- Slow-motion capturing (240 FPS) for smallest gap

Intra-Frame Gap Measurement

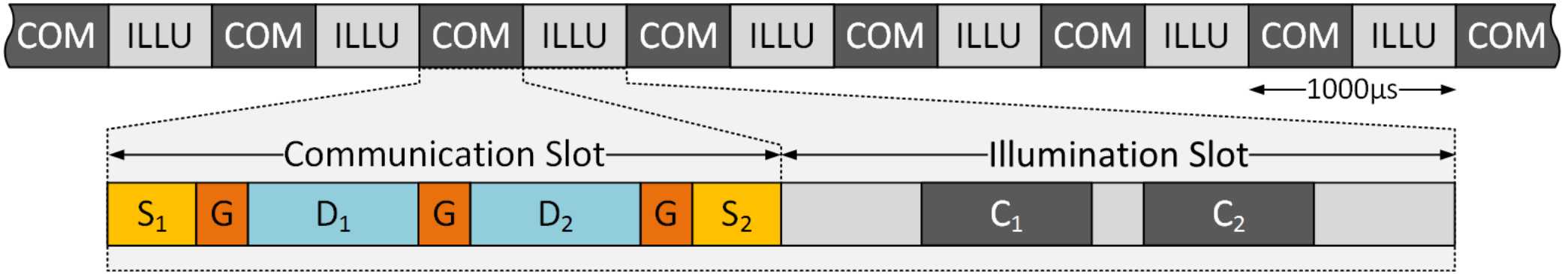


Light source is enabled for the duration of half a frame (example):

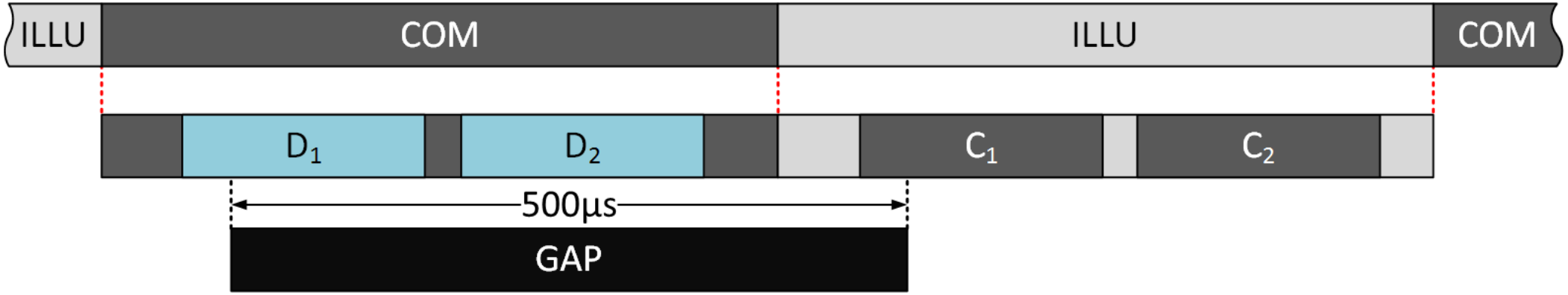
1. Light pulse is completely visible (417 pixels)
2. Light pulse is partly visible (152 pixels)
3. Remaining part of the light pulse is visible in the next frame (175 pixels)

90 pixels are missing; results in a gap of approximately **450 µs** (measured on an iPhone 6s at 240 FPS)

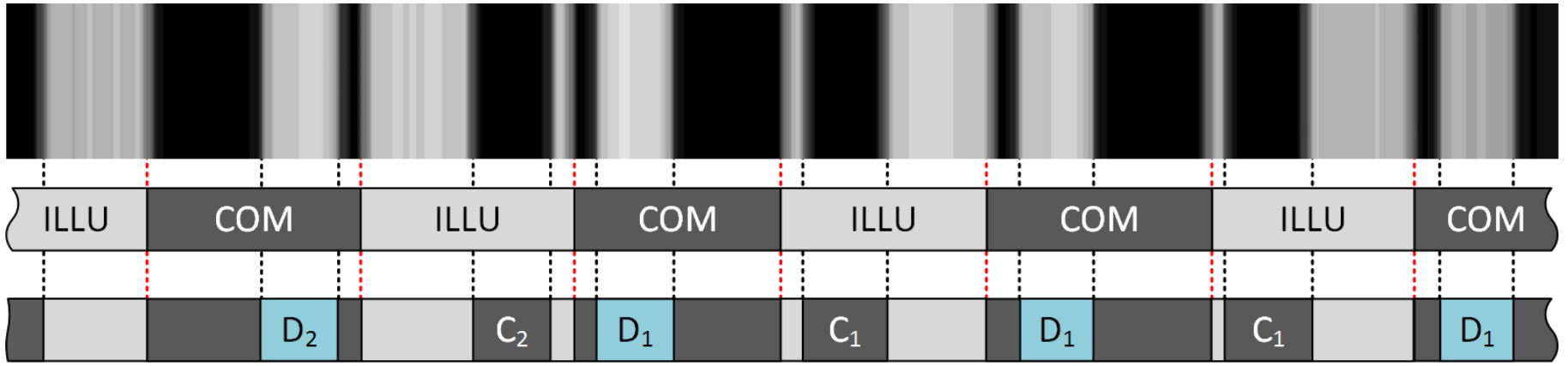
Redundancy



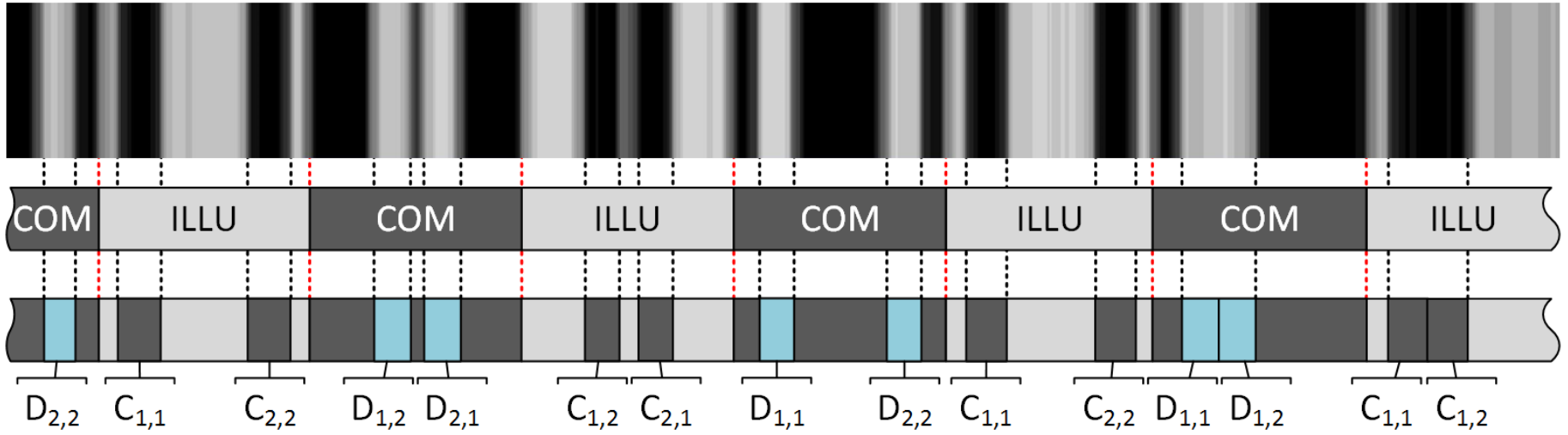
- Gap duration is (on average) shorter than 500 µs (240 FPS)
- Missing data intervals can be reconstructed



Protocol & Rolling Shutter



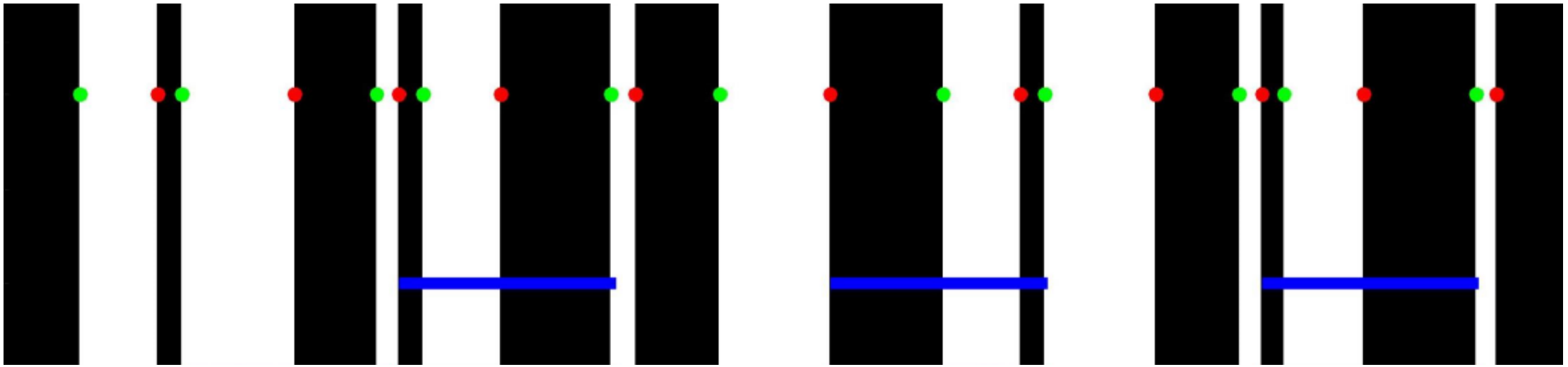
PHY mode: SINGLE



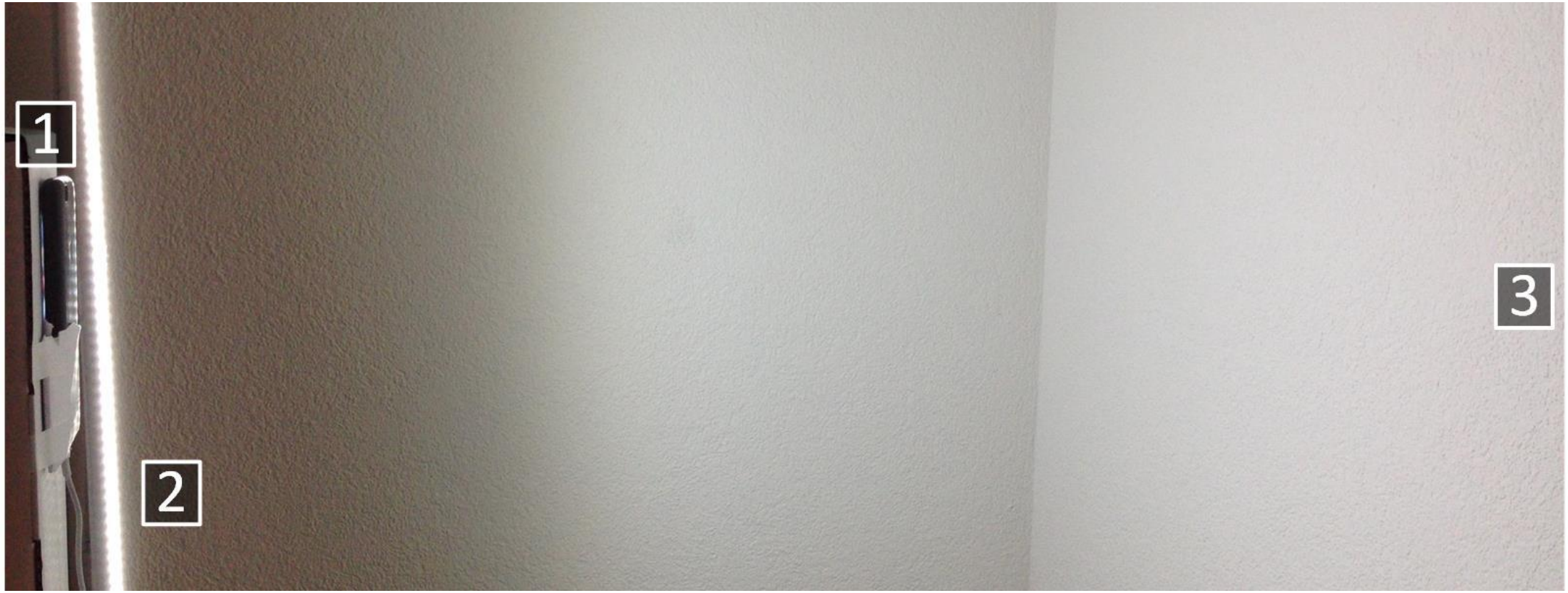
PHY mode: DOUBLE

Real-Time Decoder (iOS Application)

1. Exposure adaptation
2. Gradient detection
3. Slot detection
4. Inter-frame handling
5. Bit processing
6. Error detection / correction

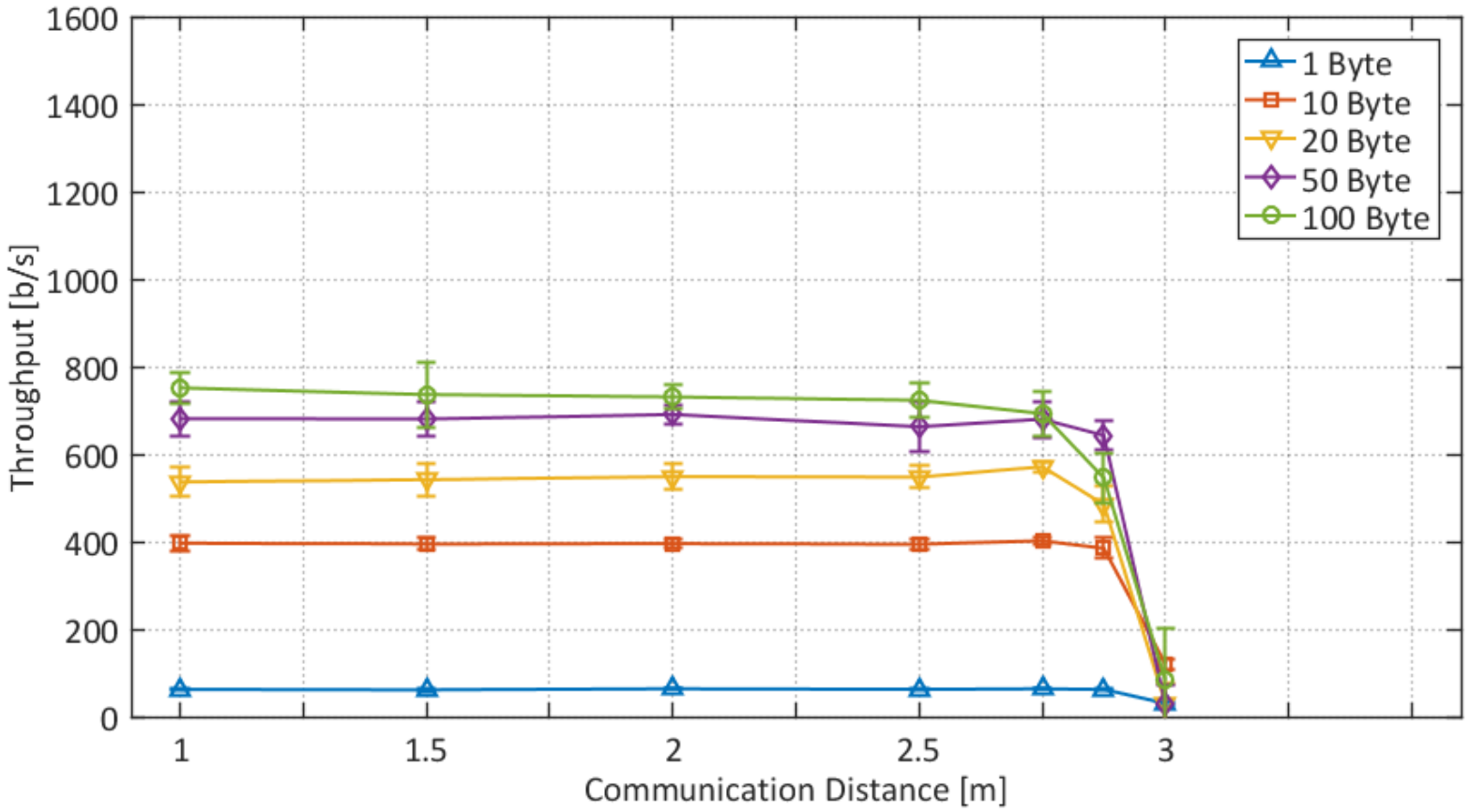


Testbed Setup



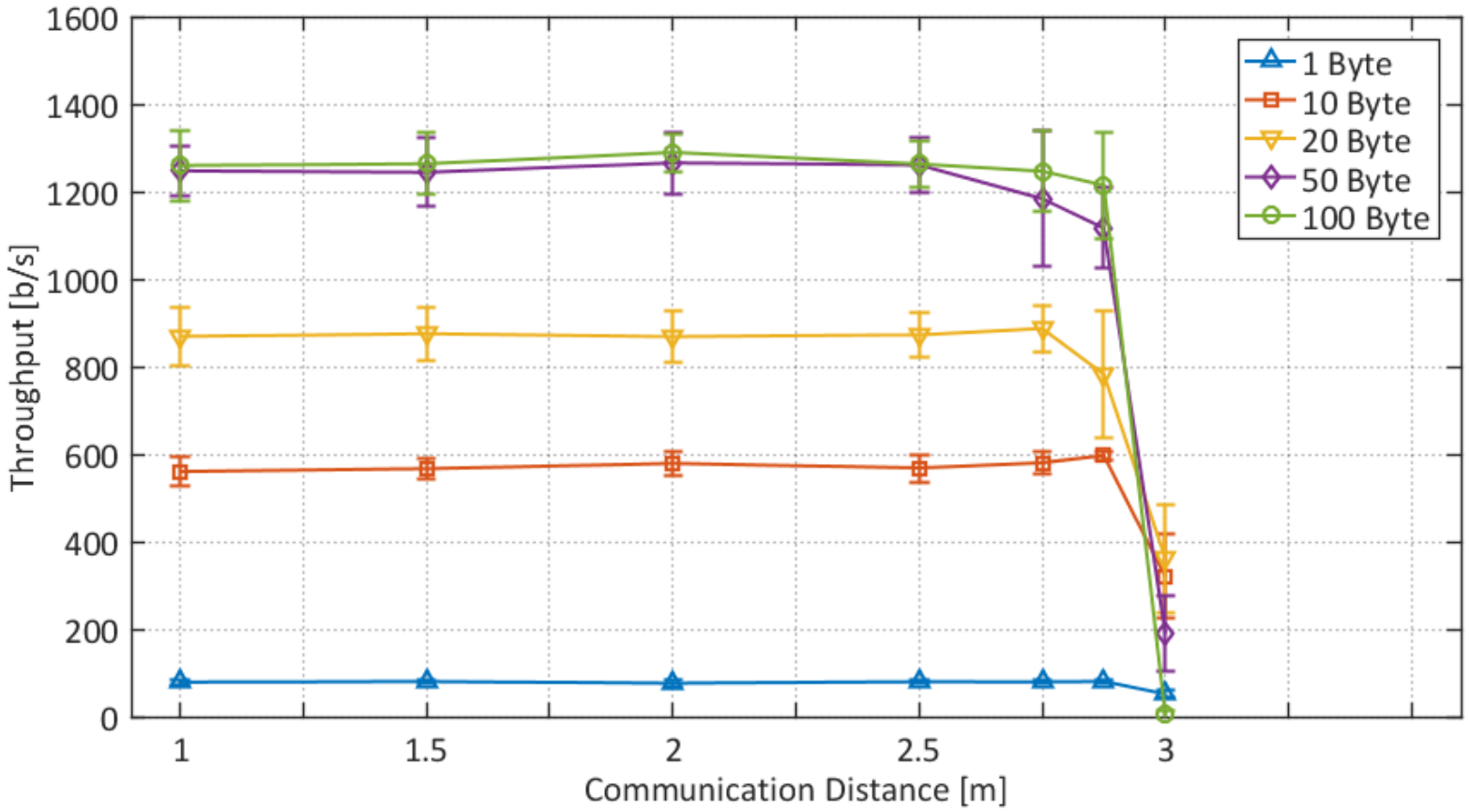
1. iPhone 6s (receiver) running the real-time decoder application
2. Light source (transmitter) connected to a microcontroller (running the VLC protocols)
3. White wall: illuminated by the transmitter and captured by the receiver

Throughput – PHY mode SINGLE



- Stable communication up to 2.75 m
- 750 b/s saturation throughput

Throughput – PHY mode DOUBLE



- Stable communication up to 2.75 m
- 1300 b/s saturation throughput

Related Work

- J. Ferrandiz-Lahuerta et al. **“A Reliable Asynchronous Protocol for VLC Communications Based on the Rolling Shutter Effect”**, 2015
  - 700 b/s, up to 3 m, reflection
- H.-Y. Lee et al. **“RollingLight: Enabling Line-of-Sight Light-to-Camera Communications”**, 2015
  - FSK, multiple light sources (direct), 90 b/s, up to 5 m
- P. Hu et al. **“ColorBars: Increasing Data Rate of LED-to-Camera Communication using Color Shift Keying”**, 2015
  - CSK, 5.2 kb/s

Conclusions

- Integration of a smartphone (camera) as a receiver into an *existing* VLC system
- Flicker-free light source
- Exploiting slow-motion capturing (240 FPS) and rolling shutter
- Real-time decoder implemented as an iOS application
- Communication distances up to 3 m
- Data throughput up to 1300 b/s