

A young child is smiling and holding a glowing light stick at a night festival. The background is filled with colorful bokeh lights in shades of blue, green, and yellow. The child is wearing a light-colored t-shirt with a graphic design.

On Philips Visible Light Communication Technology

KIVI visit to Philips Lighting

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Introduction



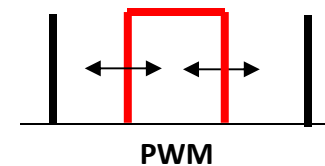
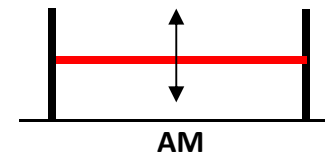
- **Transmit digital information from a luminaire to a smartphone or tablet**
 - Bits are encoded in small intensity variations of the emitted light
 - Detect bits using the camera of a smartphone

- **Illumination function of luminaire must not be compromised**
 - Light intensity variations must be imperceptible
 - Maximum light output must not suffer
 - Dimming must be possible

The Transmitter



- **The transmitter consists of an LED luminaire and its driver**
- **For a low-cost implementation, we only change the software of existing LED drivers**
 - Temporal changes of dimming levels
 - Typically, about $\pm 10\%$ change of dimming level is used
 - A few thousand changes per second is possible
 - YellowDot has a symbol frequency of 2 kHz
- **We can deal with AM dimming and PWM dimming**
 - Amplitude Modulation (AM) dimming
 - Pulse Width Modulation (PWM) dimming



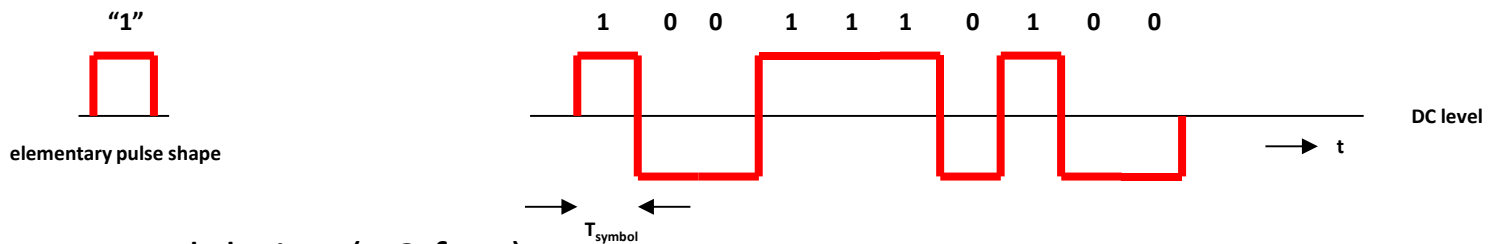
Signal Format (V2 CR-PHY)



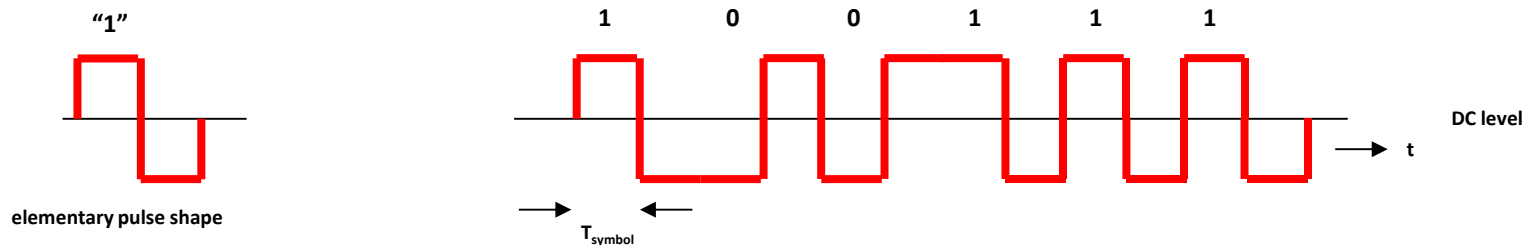
- Bits are transmitted by picking suitable waveforms for representing bits
 - Modulation codes or line codes

Well-known examples:

- Non-Return-to Zero (NRZ) modulation



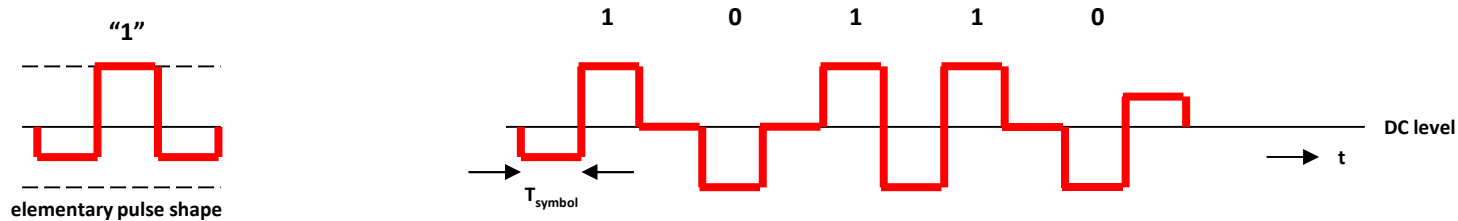
- Manchester modulation (DC-free)



Ternary Manchester



- We invented a new modulation code, especially for suppressing flicker
- Ternary Manchester (TM) modulation (DC²-free)

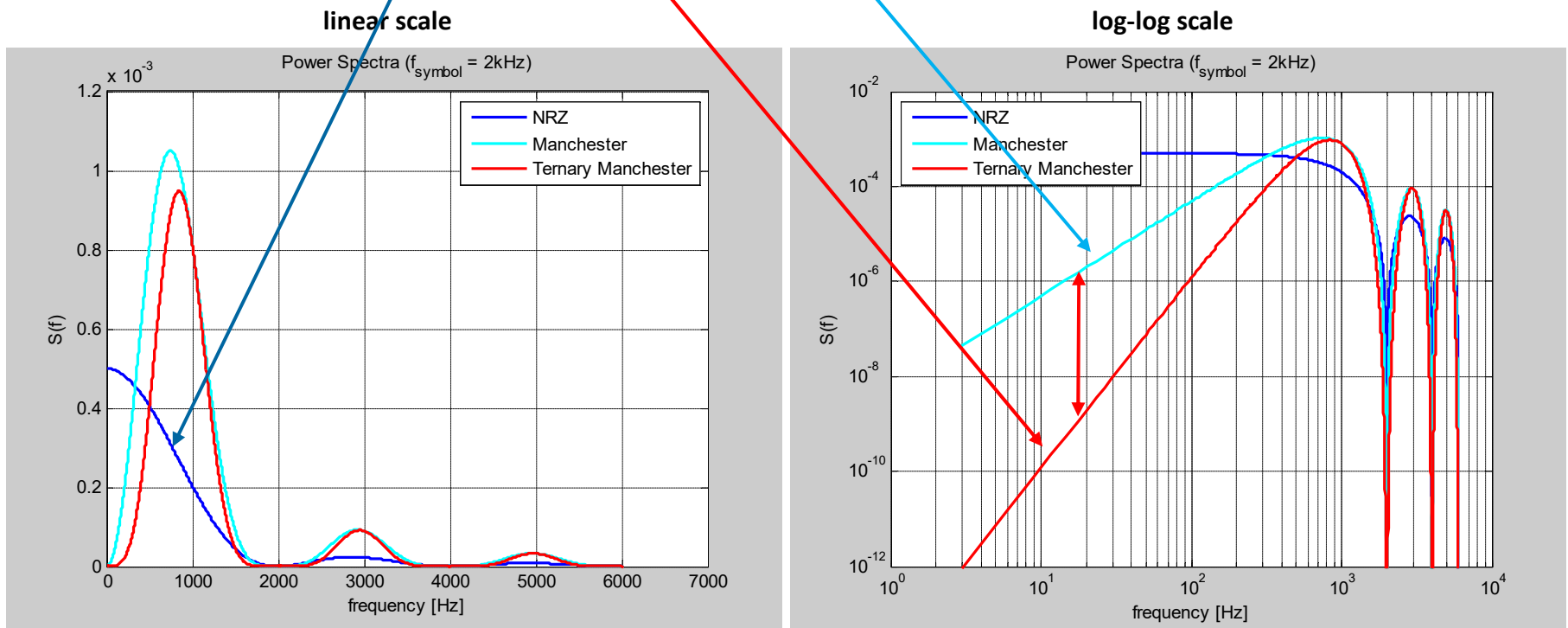


- In YellowDot, T_{symbol} equals 0.5 ms ($f_{\text{symbol}} = 2$ kHz)

Power Spectra of Modulation Codes



- NRZ: power spectrum equals classical sinc^2 curve
- Manchester: DC-free; 20 dB/octave for low frequencies
- Ternary Manchester: DC²-free; 40 dB/octave for low frequencies



Receiver



Basically, there are two types of VLC receivers:

- Using a photo detector
 - High bit rate
 - Low spatial resolution
- Using a (smartphone) camera
 - Low bit rate
 - High spatial resolution because of camera optics
 - No need for extra dedicated hardware
 - VLC receiver is an App that can be down-loaded
- In the sequel, we explain camera-based receivers

Rolling Shutter Camera



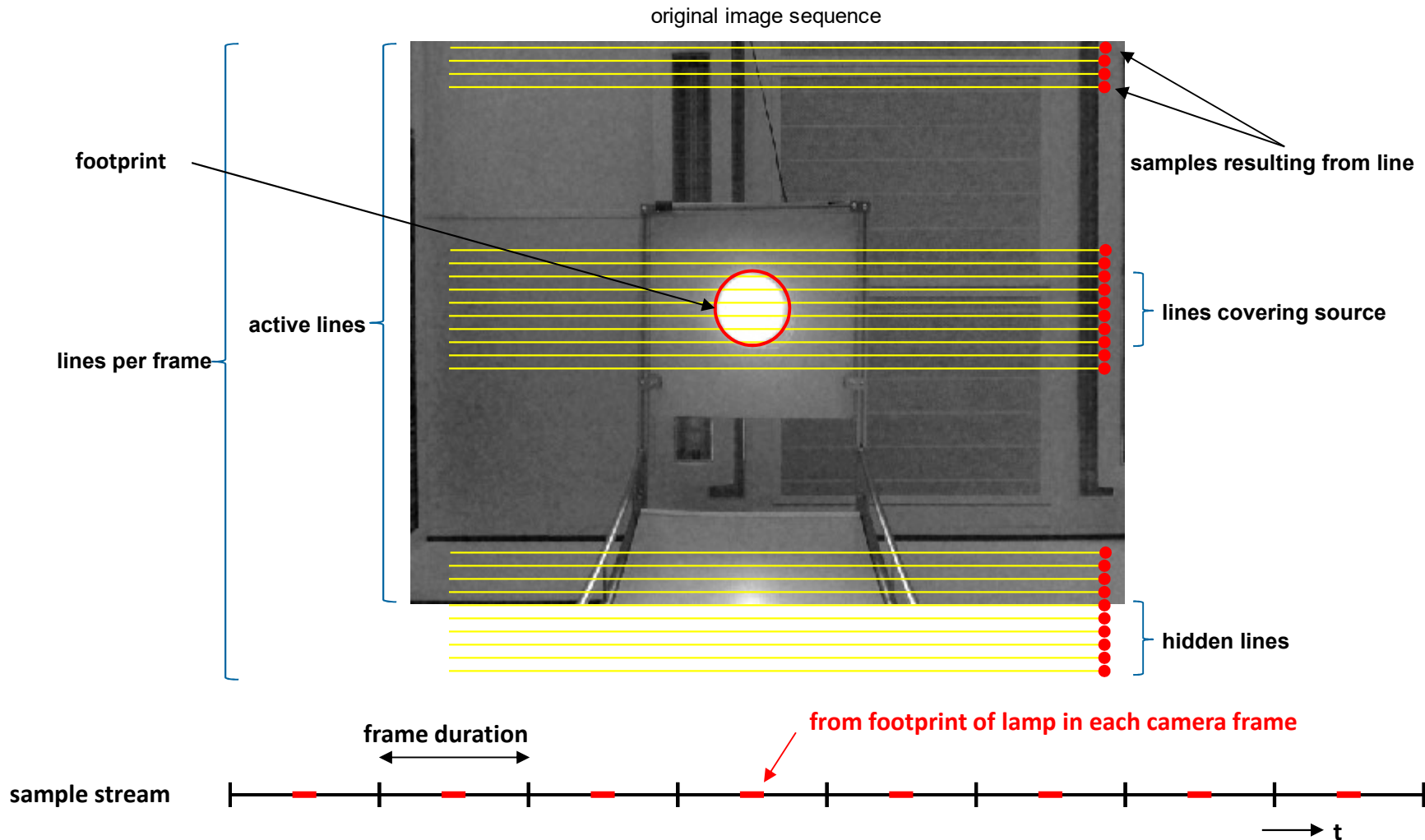
- Camera on a smartphone typically has 480 lines of 640 pixels each
- Lines are sequentially read with a line rate $f_s \approx 16 \text{ kHz}$ (30 fps)

- Sequential reading of lines leads to “rolling shutter” effect
 - Undesirable for photography
 - For us, it enables a fast sampling of a light source



- The pixels of each line have an exposure time of T_{exp} immediately preceding the moment of read-out
 - typically, T_{exp} ranges from $1/30$ to $1/16000$ [s]
 - each pixel in a line sees average light of T_{exp} seconds
 - ➔ smearing of coded light waveforms

Operation of Rolling Shutter Camera

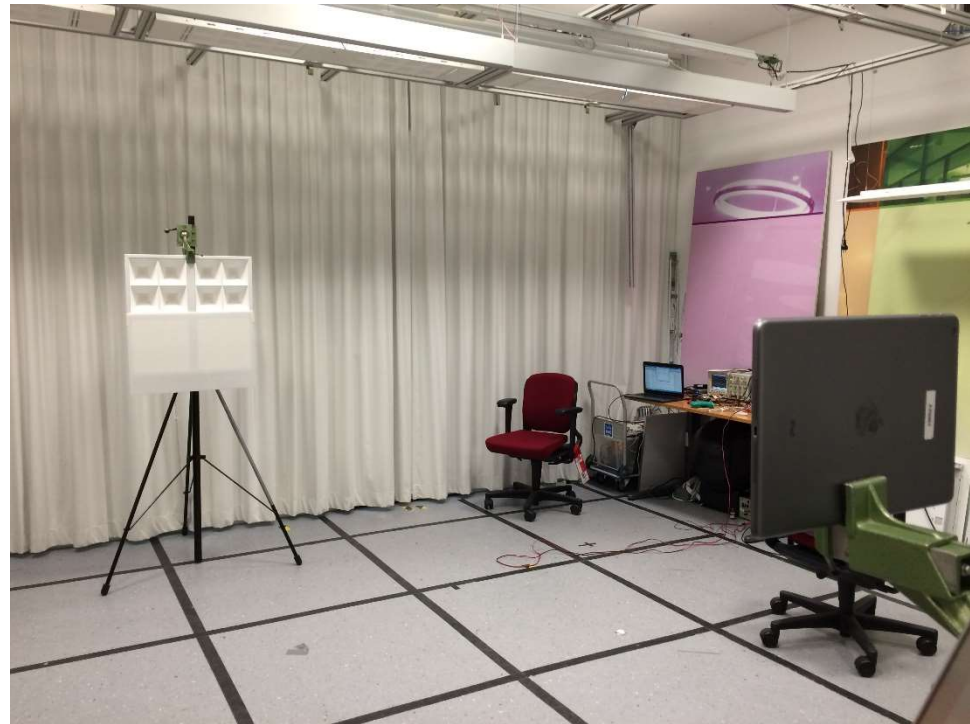


Demo Rolling Shutter and Coded Light



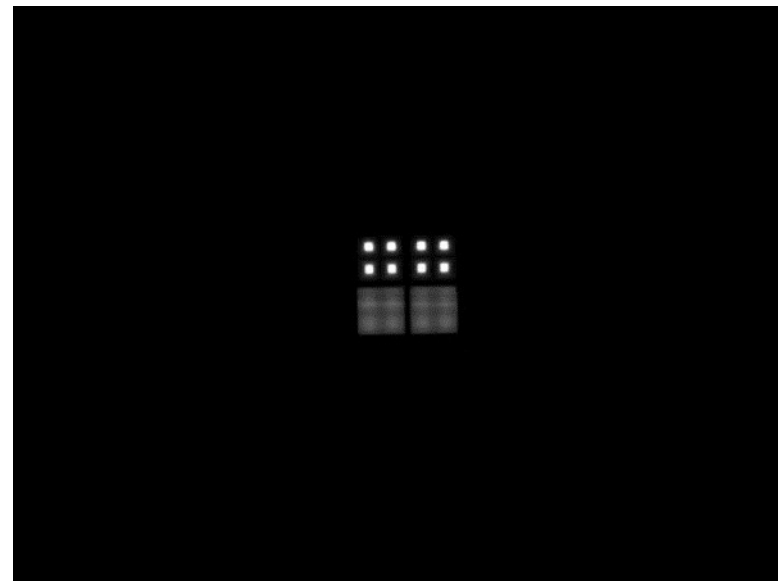
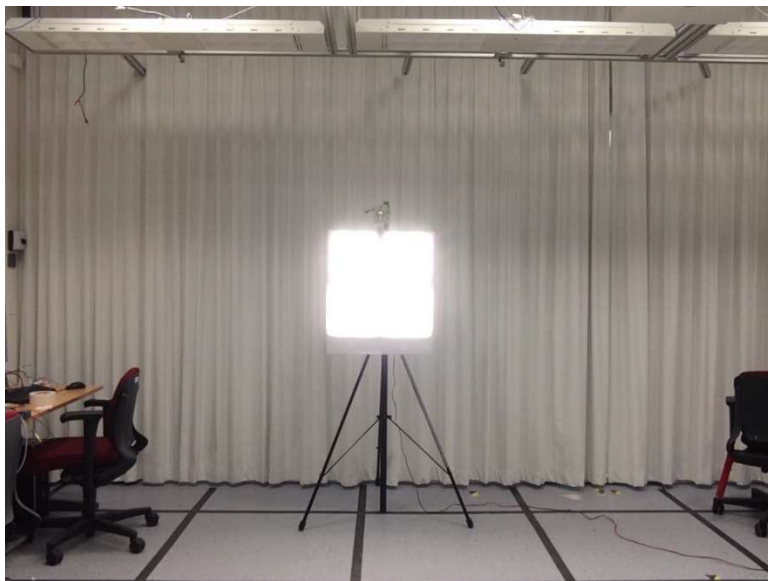
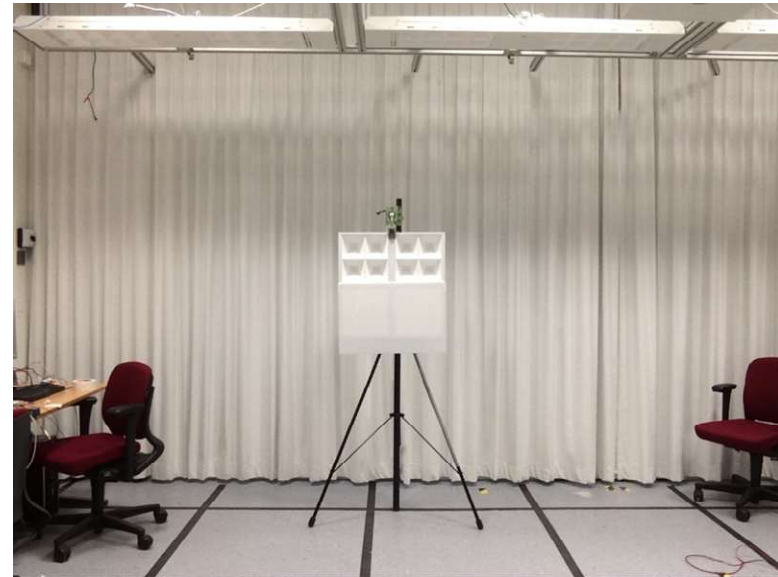
Experimental set-up:

- Luminaire: Power Balance (4 x 4 cups) on a standard in background left
 - Lower half covered by semi-transparent plastic sheet
- Tablet (iPad) recording device in foreground right
 - Front camera looking at luminaire
- Distance luminaire – tablet ≈ 4 m

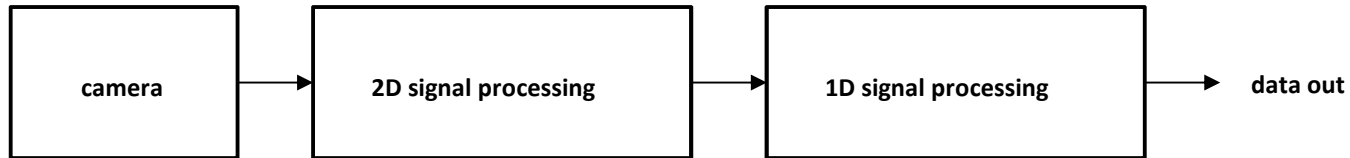


iPad Recordings

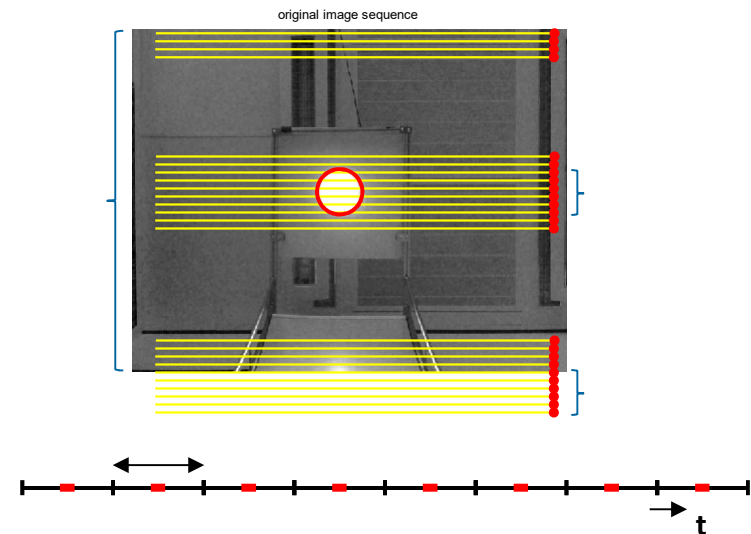
- Power Balance 4 x 4
- Footprint size = 0.17
- Message duration: 36.5 ms
(> 1 frame @ 30 fps)
- 20% modulation depth



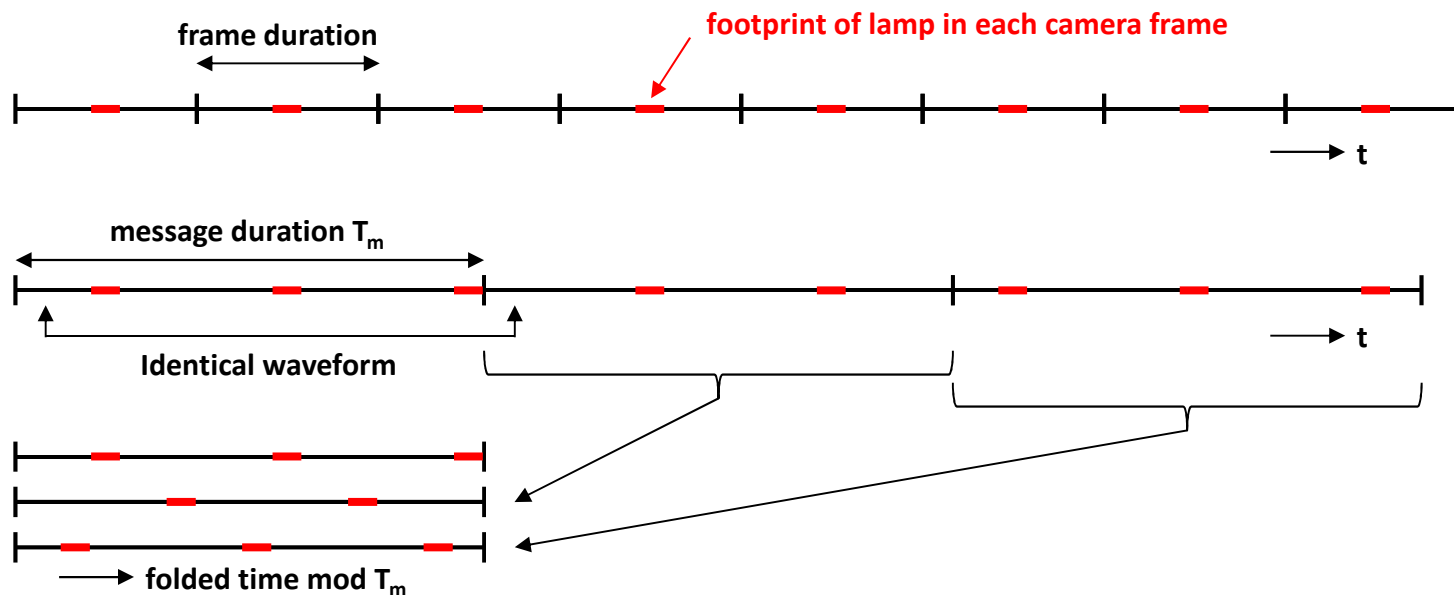
Signal Processing



- 2D signal processing on images (frames)
 - Segmentation of images into lamps
 - Motion compensation
 - Computing marginal 1D signals
- 1D signal processing
 - Background subtraction
 - **Message Reconstruction** ←
 - Equalization by Robust Wiener filtering
 - Synchronization
 - Bit detection



Message Reconstruction (stitching)



- **Message of a given luminaire is cyclically repeated**
 - We usually need between 10 and 60 frames for reconstruction of messages of 24 bits
 - Depends mainly on
 - size footprint of lamp
 - deviation of the transmitter clock
 - **if message duration is chosen carefully** (folded footprints need to cover the message)

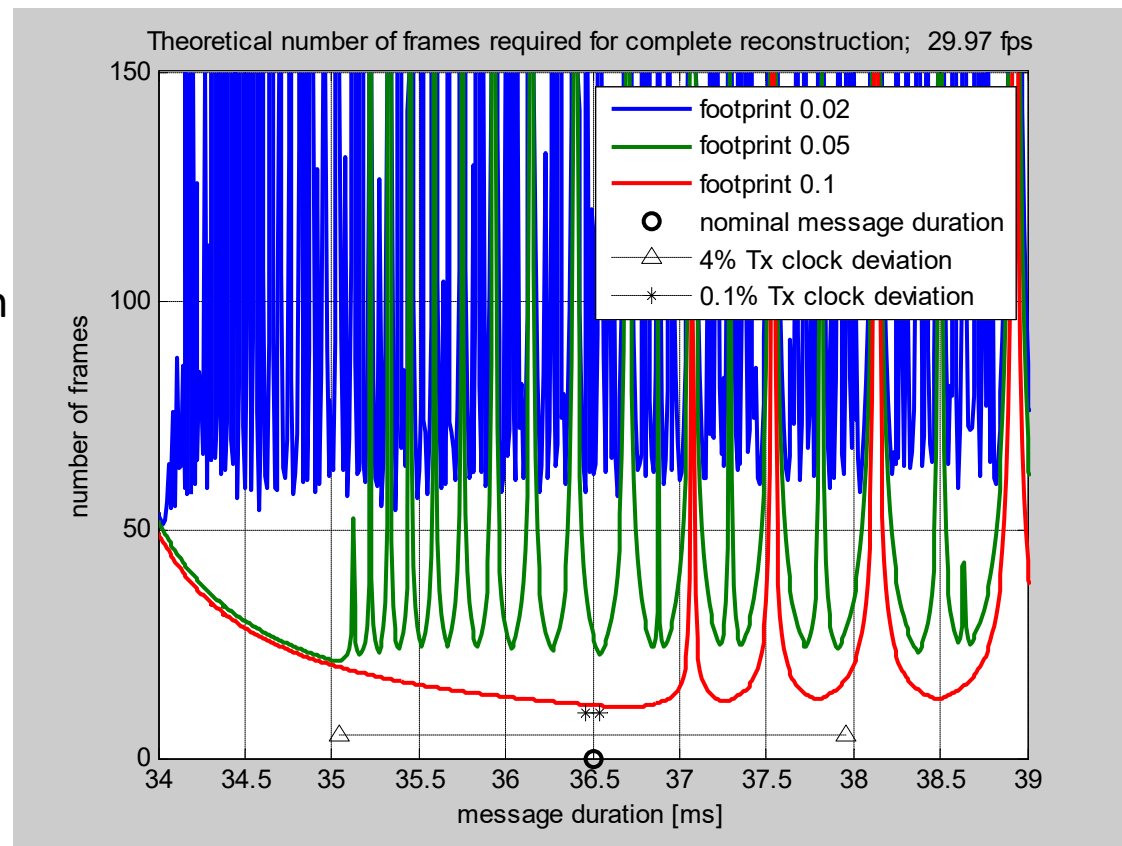
Stitching Singularities



- If the quotient of message duration and frame duration is a rational number, it may take an infinite number of frames to cover the message (singularity)

- Depends also on the size of the footprint

- Nominal message duration of YellowDot equals 36.5 ms
- Tx having a ceramic clock (0.1% clock deviation) enables footprint of 0.05



Personal Control

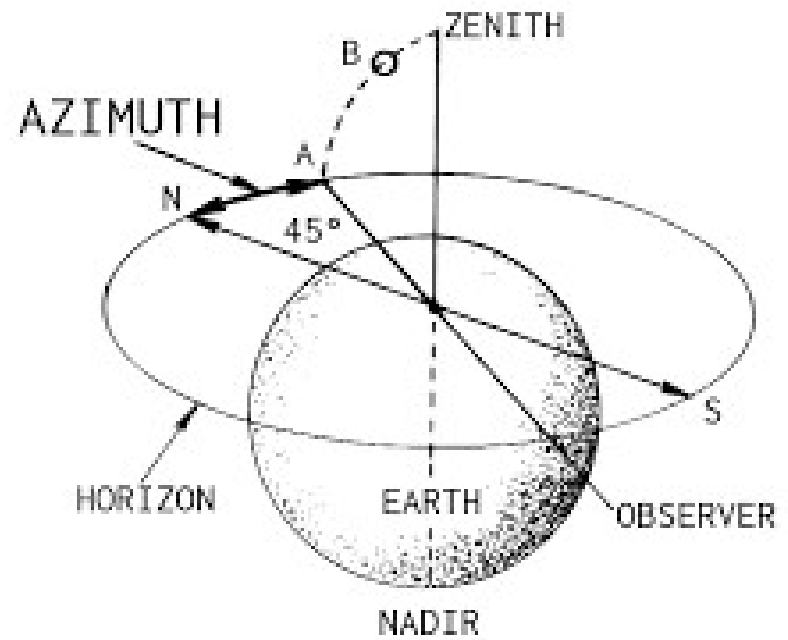


Personal Control



<https://www.youtube.com/watch?v=ToF0dDUa78o>

Indoor Positioning



Indoor Positioning



<https://www.youtube.com/watch?v=E4fJ6ZzAl7E>

