無線網路概論
Intro. to Wireless Internet

Lecture 14 – Visible Light Communications

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YZU CSE

Lecture Material

- Partial from Princeton COS 463: Wireless Networks
  - https://www.cs.princeton.edu/courses/archive/spring18/cos463/index.html
- "Visible Light Communication: Concepts, Applications and Challenges," IEEE Communications Surveys & Tutorials, Vol. 21, No. 4, pp. 3204-3237, 2019.
- "A framework for simultaneous message broadcasting using CDMA-based visible light communications," IEEE Sensors Journal, Vol. 15, No. 12, pp. 6819-6827, 2015.

VLC

- https://youtu.be/iHWIZsIBj3Q

History

- Visual telegraphy - the Polybius square
  - https://youtu.be/WrNDeYjcCJA

History

- Optical telegraph by Charles Chappe
  - 92 combinations of the regulator and indicators

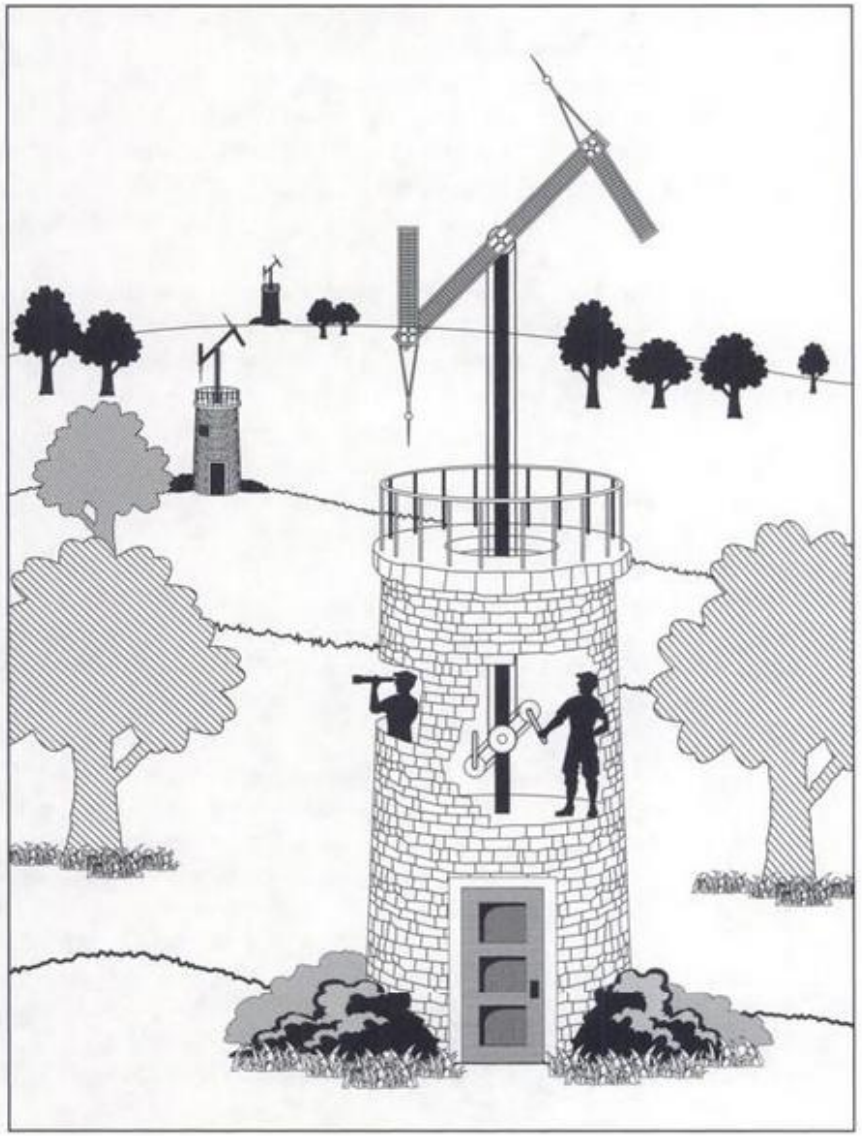
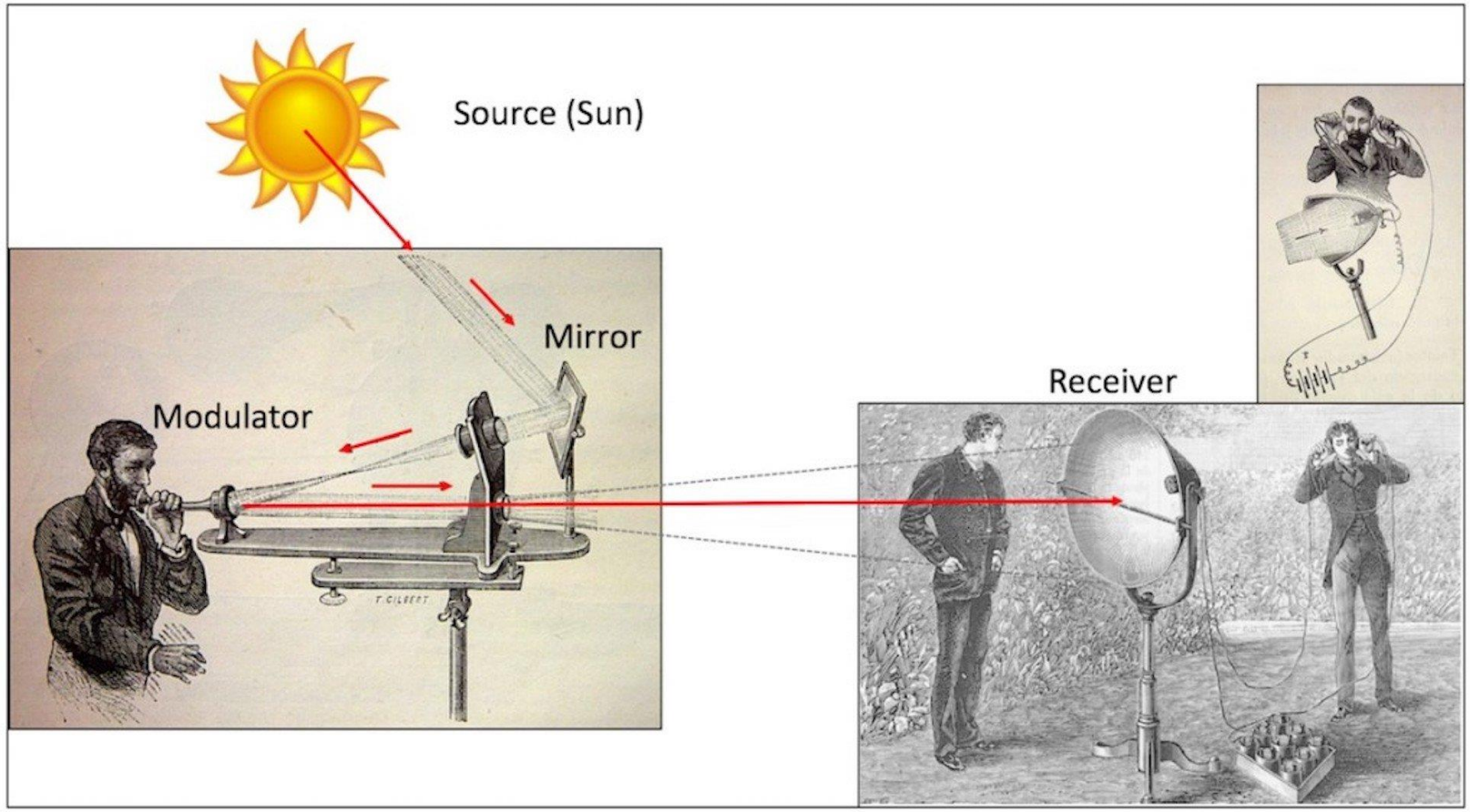


Figure 19. Semaphore towers. Previous to Claude Chappe's series of evenly spaced semaphore towers, communication was no faster than it was during antiquity. But with a little practice, Chappe's semaphore operators learned to transmit a simple sign over many miles in just a matter of minutes.

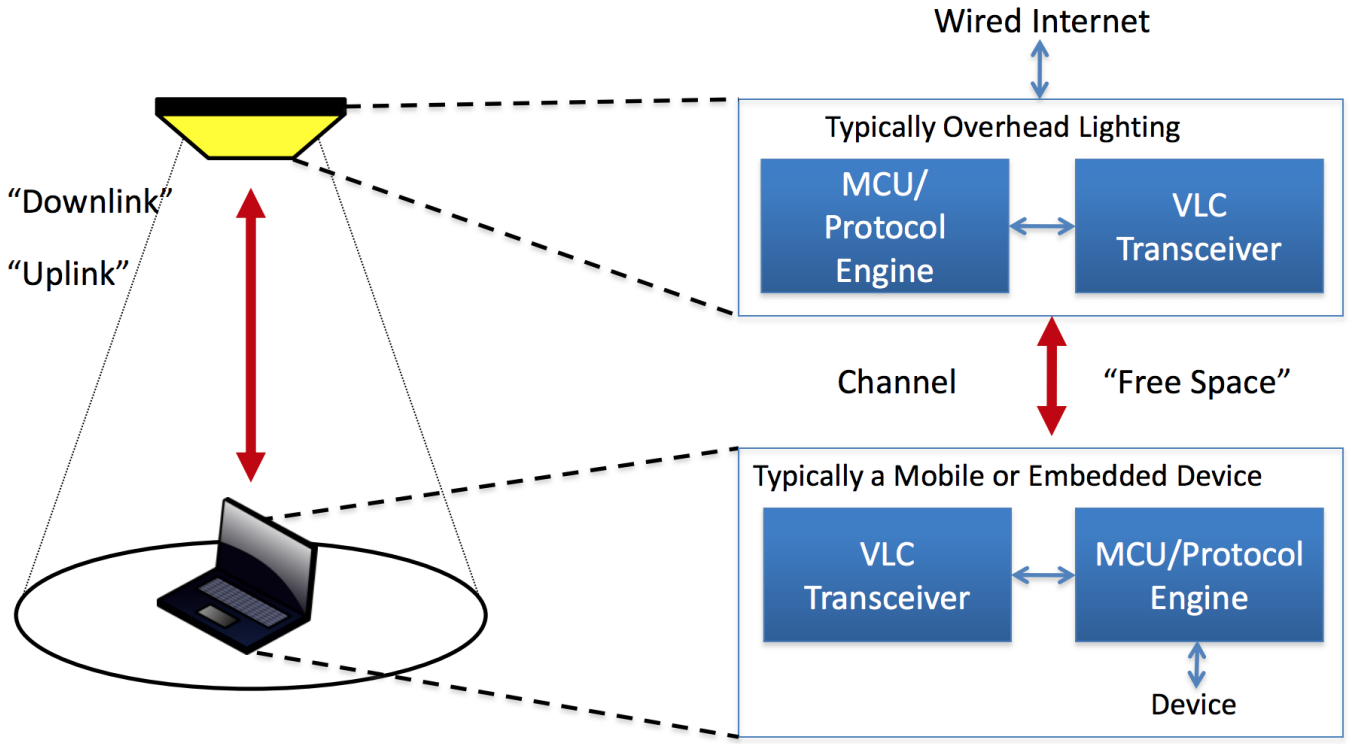
History

- Photophone invented by Alexander Graham Bell



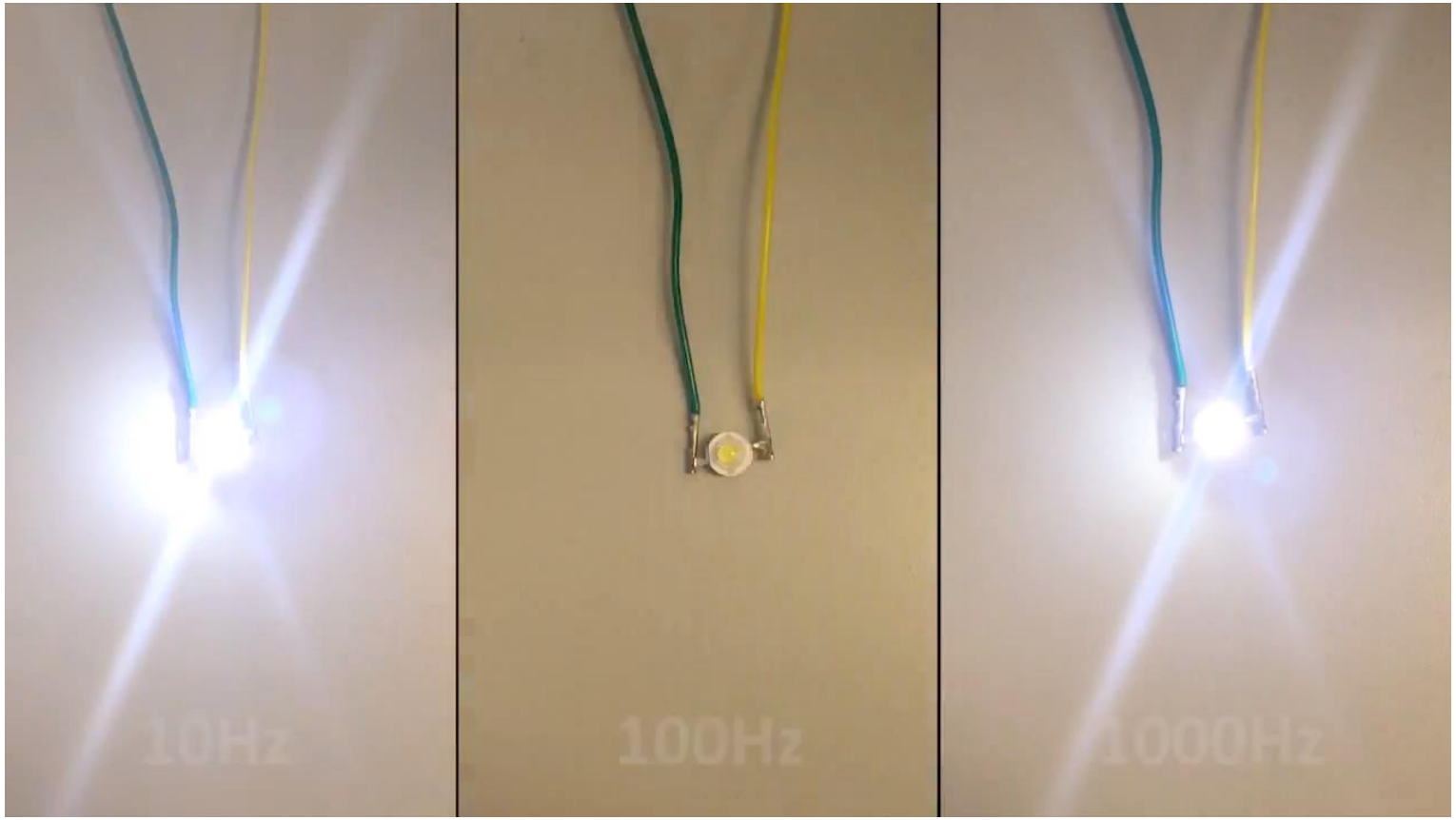
What is VLC

- Visible light communication (VLC)
  - visible light source as a signal transmitter
  - air as a transmission medium
  - appropriate photodiode as a signal receiving component



What is VLC

- Key idea behind VLC
  - Eye cannot detect fast light switching but semiconductor- based photodetector can do



What is VLC – Light Source

Incandescent bulb

Lumens/W: 10-18

- First industrial light source
- 5% light, 95% heat
- Few thousand hours of life

Efficiency: 5%

Power usage: > 40%

Fluorescent lamp

Lumens/W: 35-100

- White light
- 25% light
- Lifetime ~10,000s hours

Efficiency: 25%

Power usage: 20%

Light emitting diode (LED) – since 1990s

Lumens/W: 35-150

- Compact and 50% light
- Uses 2-17 watts of electricity
- More than 100,000 hours lifespan

80 %

Efficiency: 60%

Power usage: 10%

What is VLC – Light detector

- **PIN photodiode**
  - low cost, large area
  - limited sensitivity

- **Image sensors**
  - **Charge-Coupled Device (CCD)**: low cost, slow due to serial read-out

Motivation of VLC

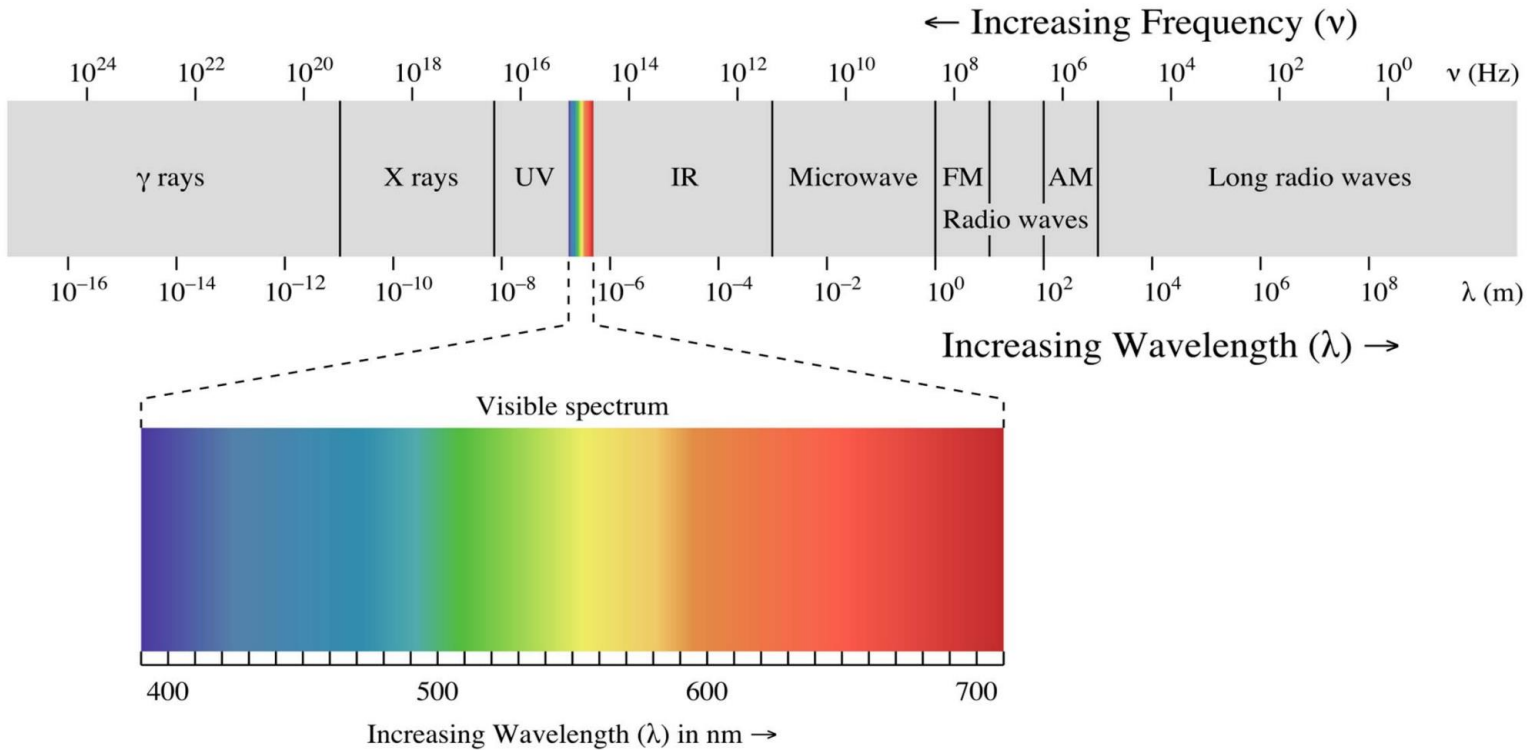
- Privacy-preserving
- Resilient to Interference
- Radio spectrum crunch
  - Ever-growing user demands meet limited radio spectrum

Related Terms

- Visible Light Communication (VLC)
- Optical Wireless Communications (OWC)
  - infrared, visible or ultraviolet
- Free-Space Optical Communication
  - large-scale transmissions, such as communications between satellites and towers on Earth
- Light Fidelity (Li-Fi)
  - two-way multi-user communication and high speed

Looking into VLC spectrum

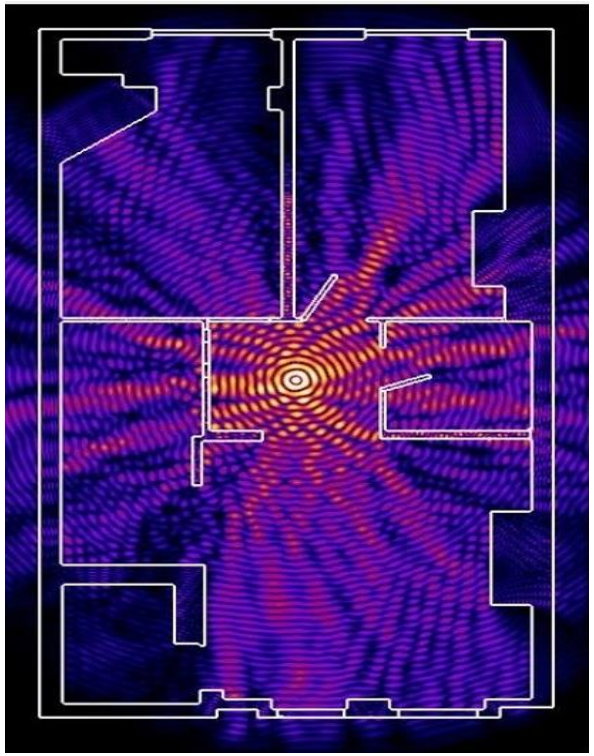
- VLC has a large frequency band
  - 390 nm – 700 nm in wavelengths
  - 430 – 770 THz in frequency

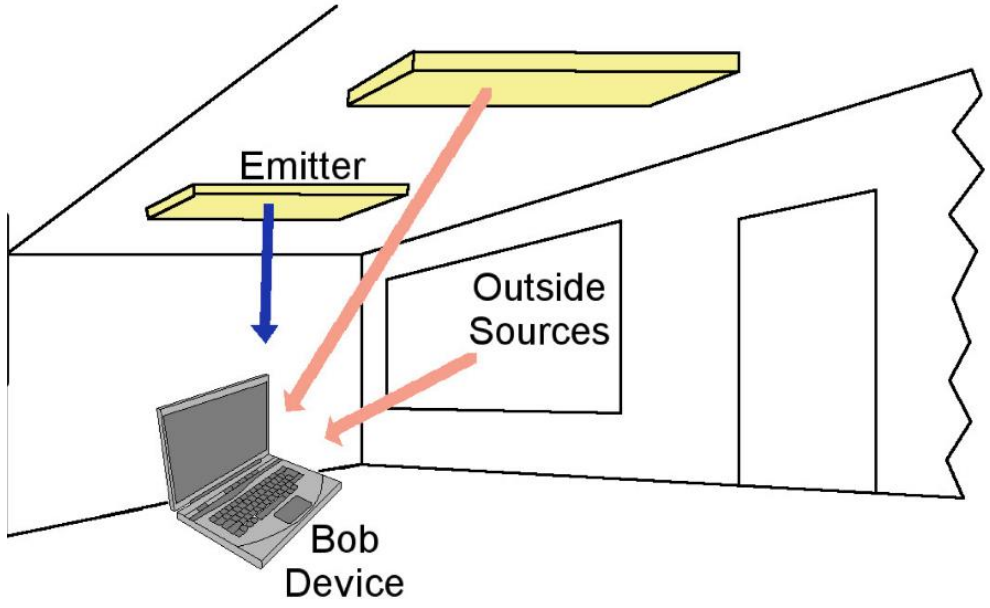


Key Difference from RF

- RF communication works in a Non-line-of-sight environment
- VLC requires Line-of-sight between the transmitter and the receiver

RF signals





RF vs. VLC

	Wi-Fi	NFC	Bluetooth	VLC
Spectrum	2.4 GHz / 5 GHz	13.56 MHz	2.4 GHz	~ 400~THz
Infrastructure	Access Point	Device	Device	Illumination
Ambient interference	Low	Low	Low	High
Security	Limited	Limited	Limited	High
Coverage	High	Low	Low	Limited
System complexity	High	High	High	Low
Electromagnetic interference	Yes	Yes	Yes	No

VLC Advantages

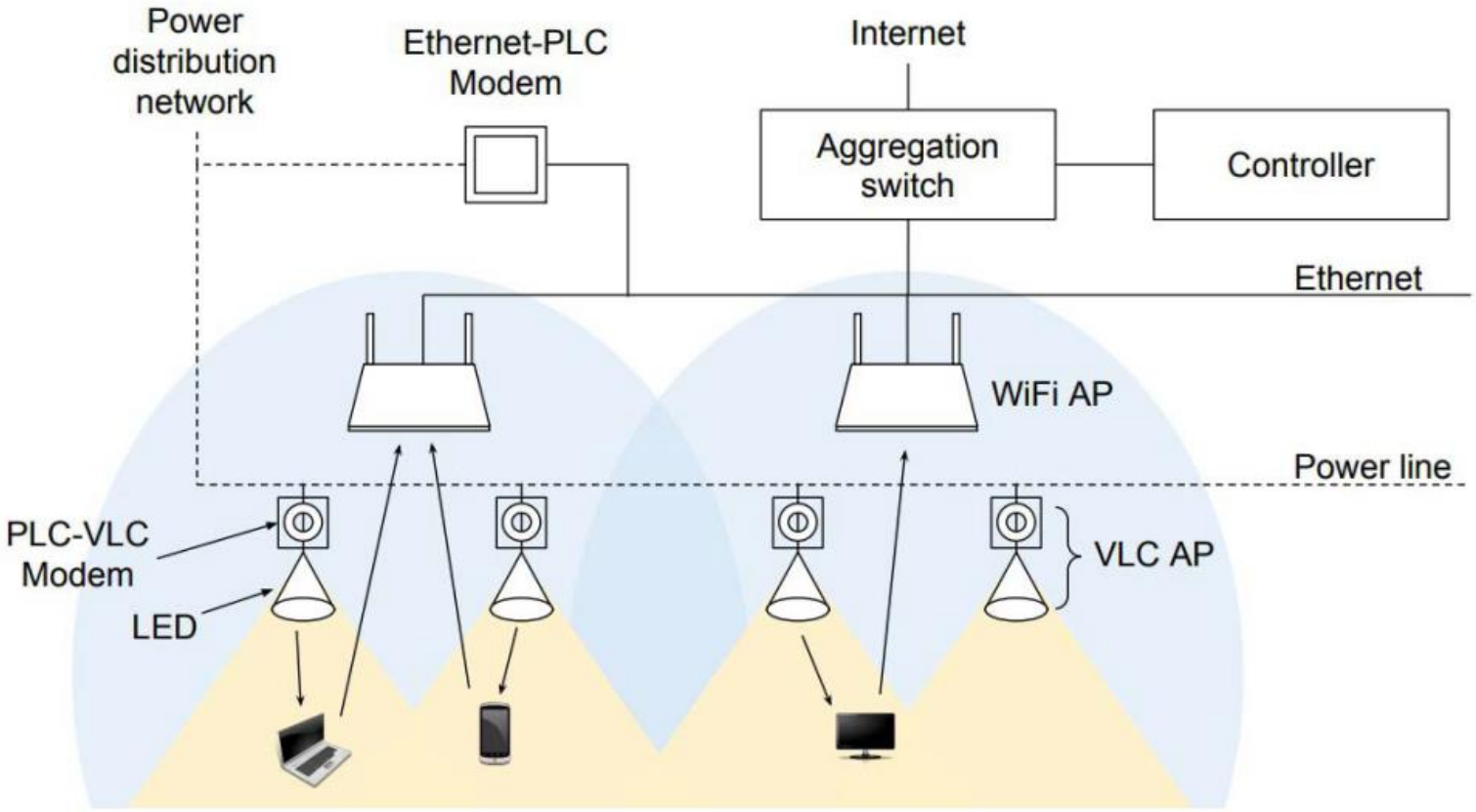
- The use of existing infrastructure also to provide communication services.
- The size of the spectrum compared to radio frequency
  - The spectrum of visible light is totally free, generating diverse commercial and academic possibilities
- Light offers security advantages when compared to radio waves
- High frequency of waves (in the THz magnitude), which allows for very high data rate communication

VLC Systems

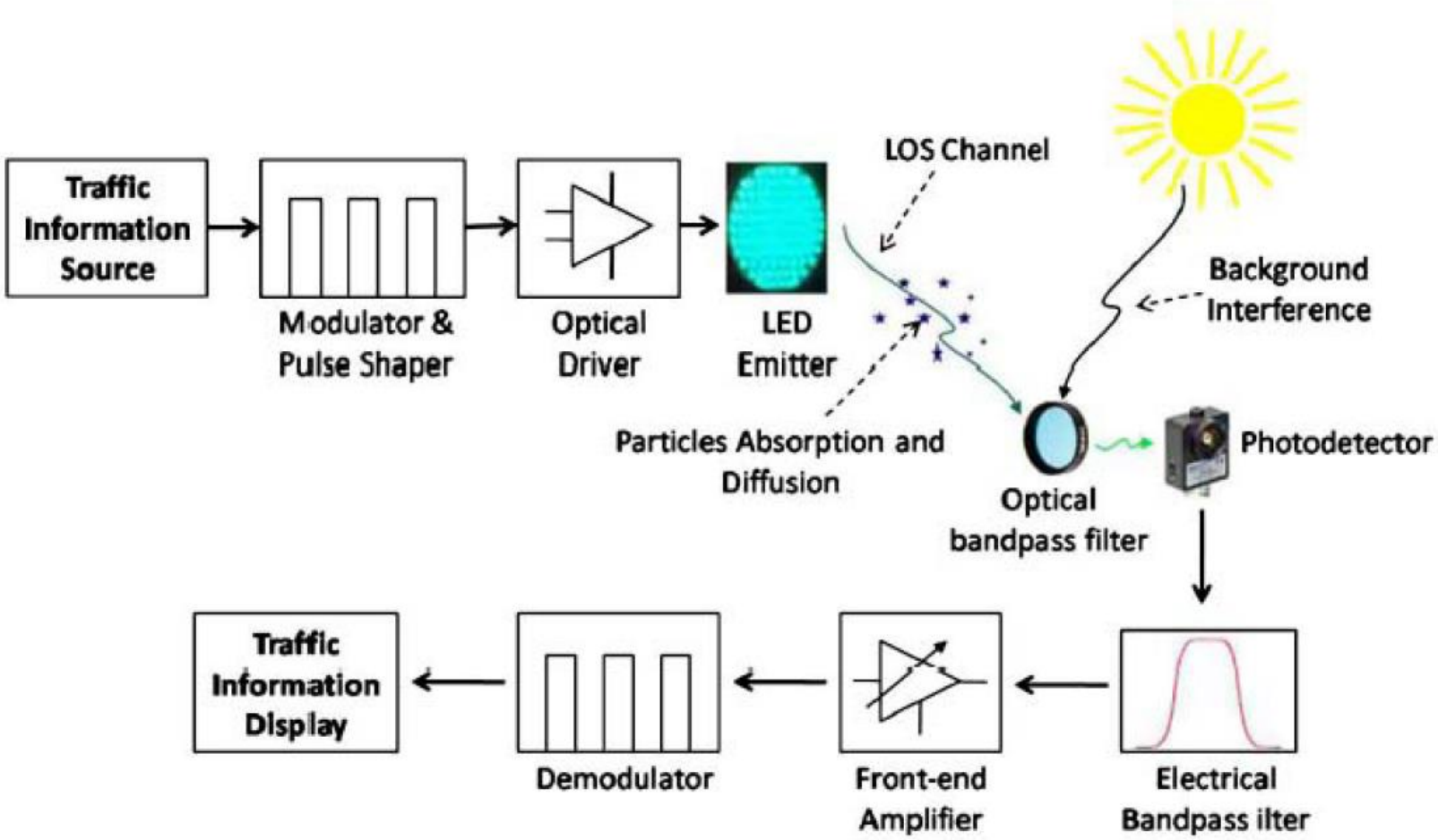
- LiFi-XC
- https://www.youtube.com/watch?v=yzWNB9CkpmA

VLC Systems

- PLifi
  - The hybrid platform PLifi was created with the purpose of joining Wi-Fi to VLC, in an internal environment

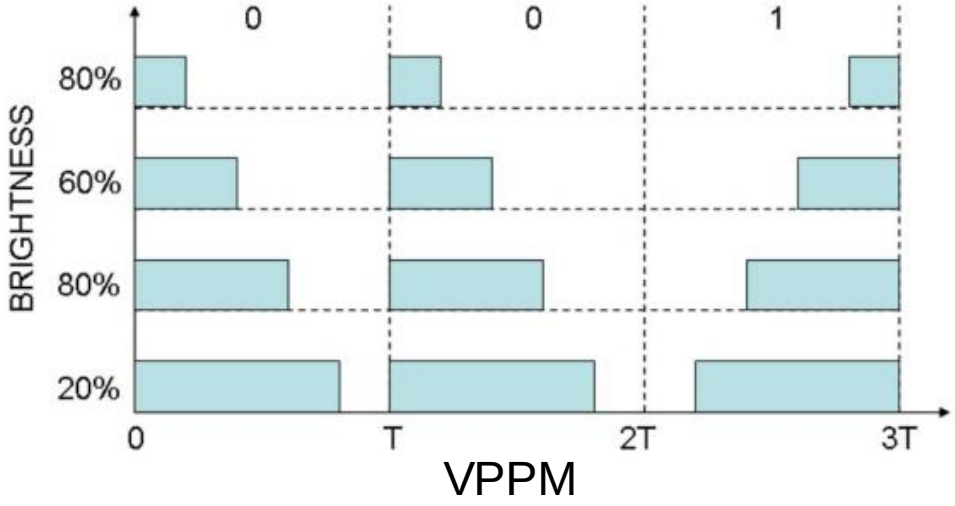


Communication Architecture

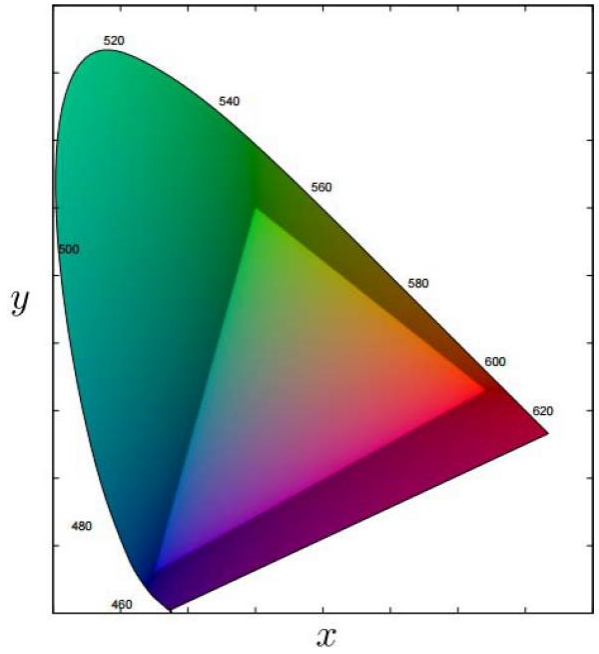


VLC PHY

- Modulation schemes
  - OOK (On-Off Keying)
  - Variable Pulse Position Modulation (VPPM) (PWM)
  - CSK (Color Shift Keying)
  - OFDM (Orthogonal Frequency Division Multiplexing)
- Requirements
  - dimming
  - flickering



VPPM



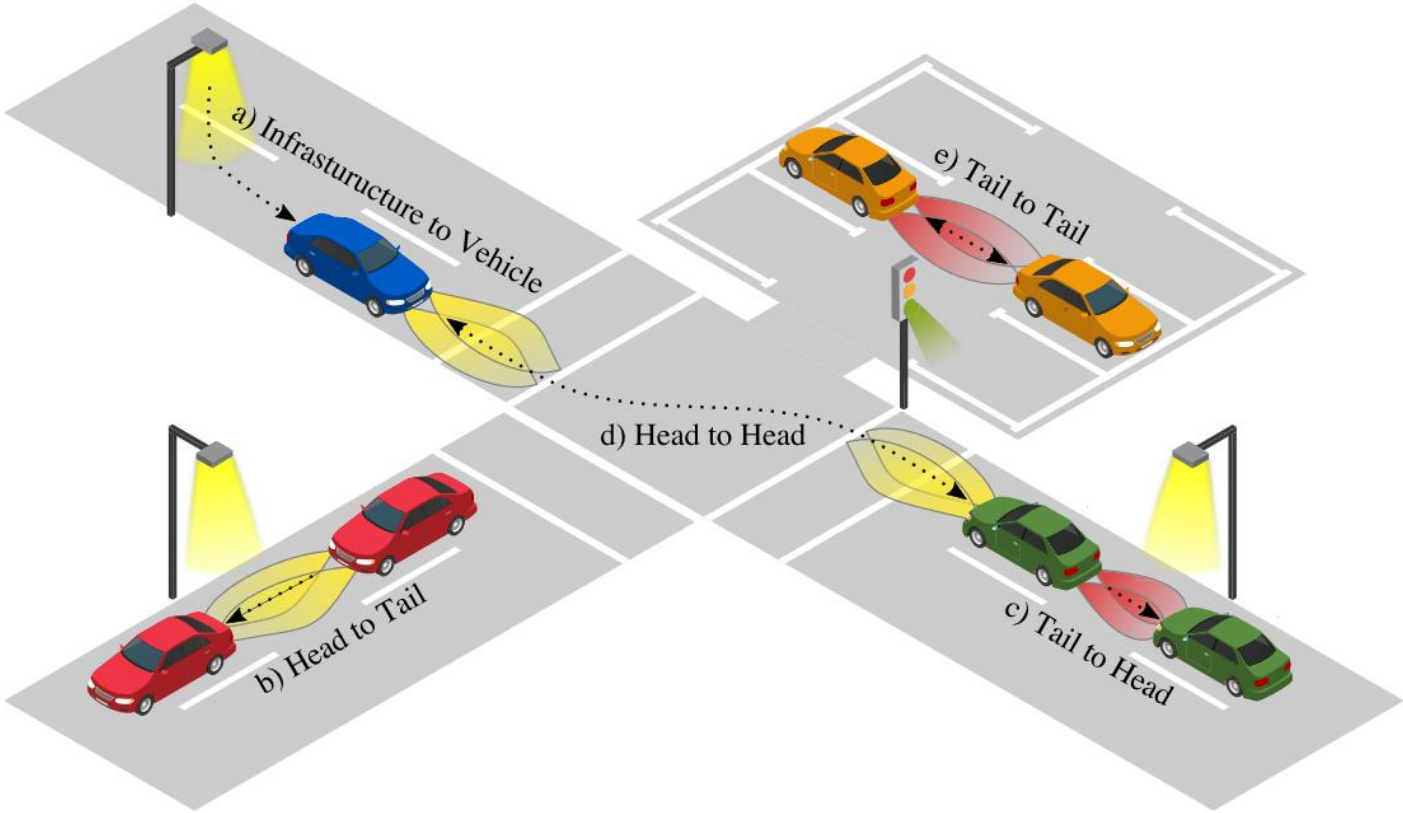
CSK

VLC MAC

- TDMA
- SDMA
- CSMA
- OFDMA
- CDMA

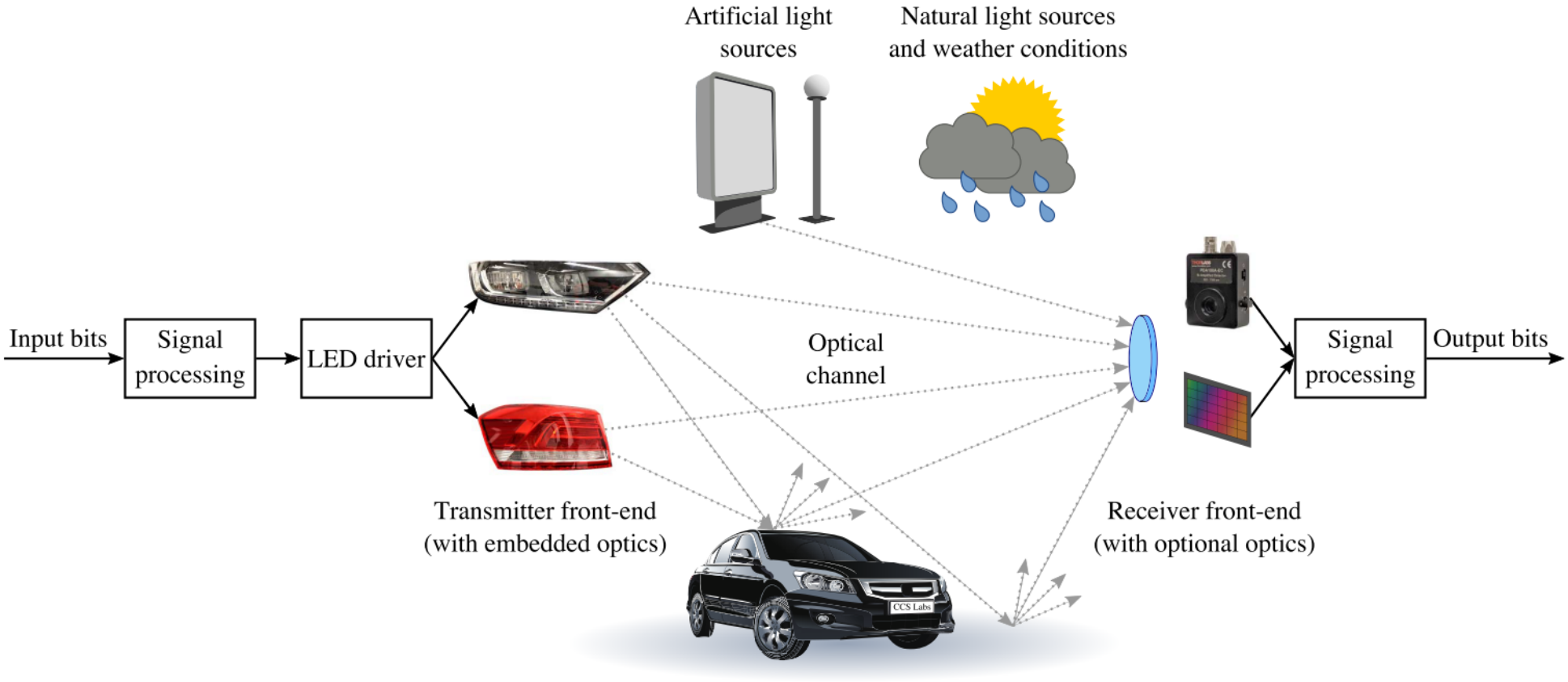
VLC Applications

- Vehicular VLC



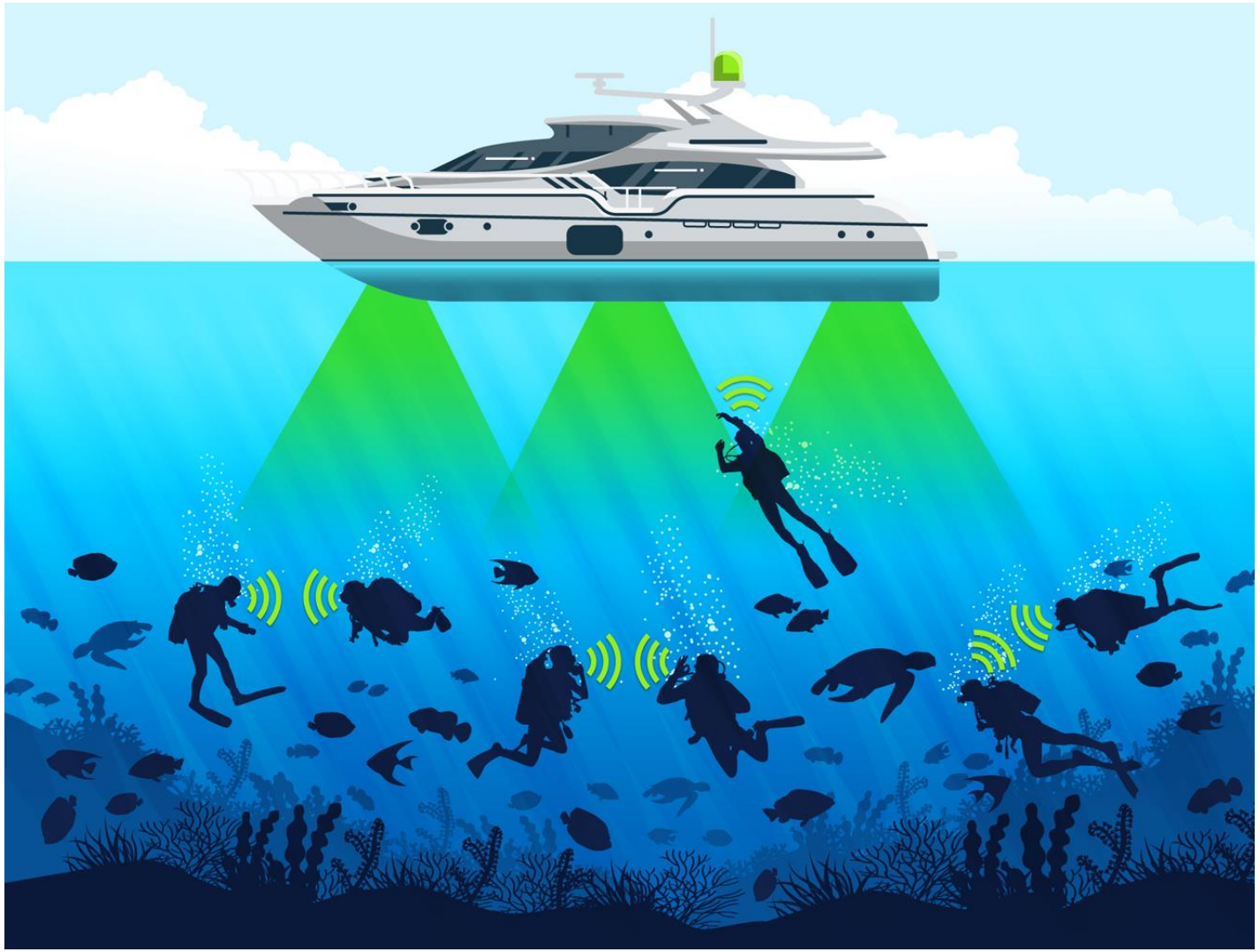
VLC Applications

- Vehicular VLC



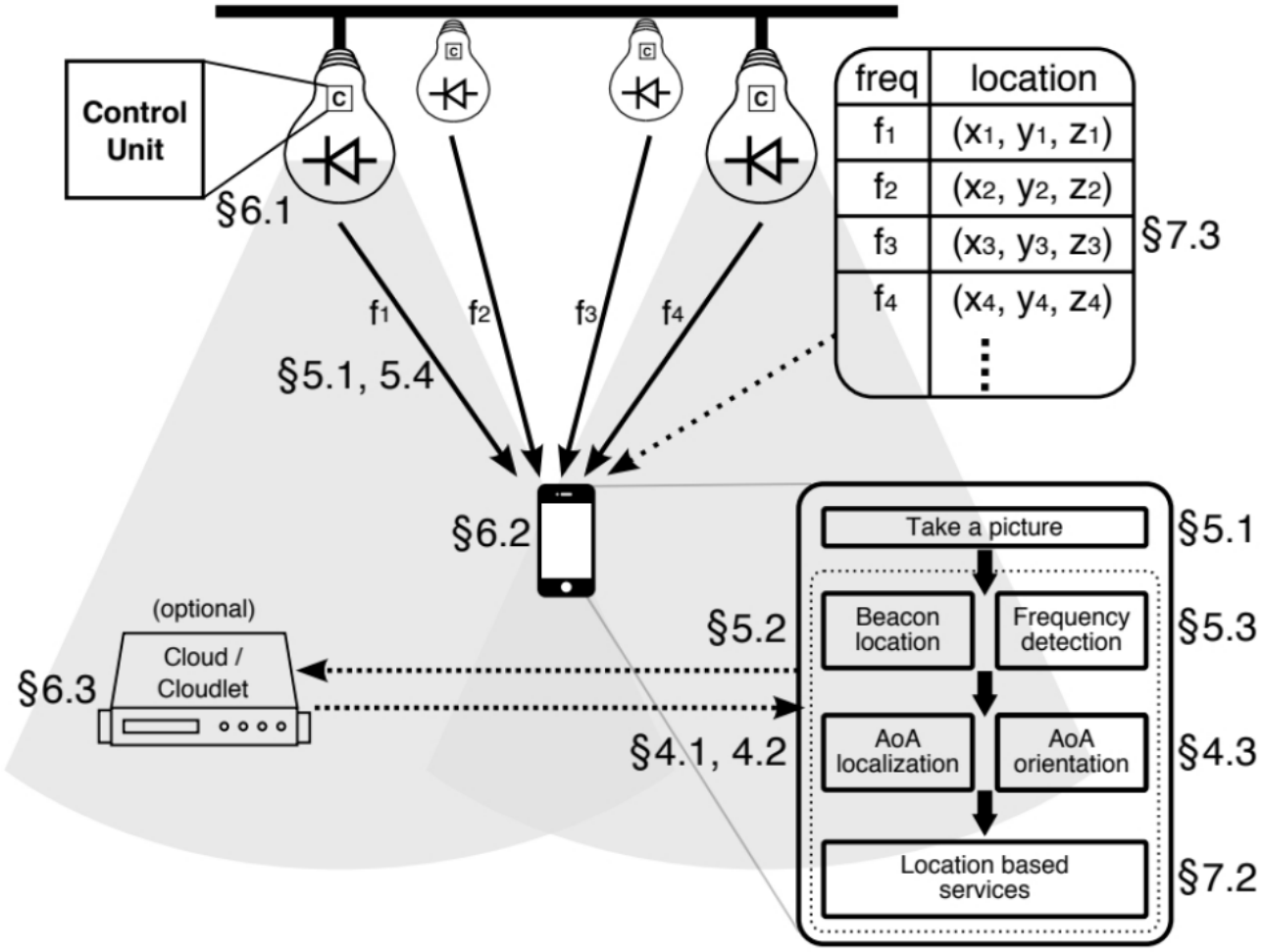
VLC Applications

- Underwater VLC



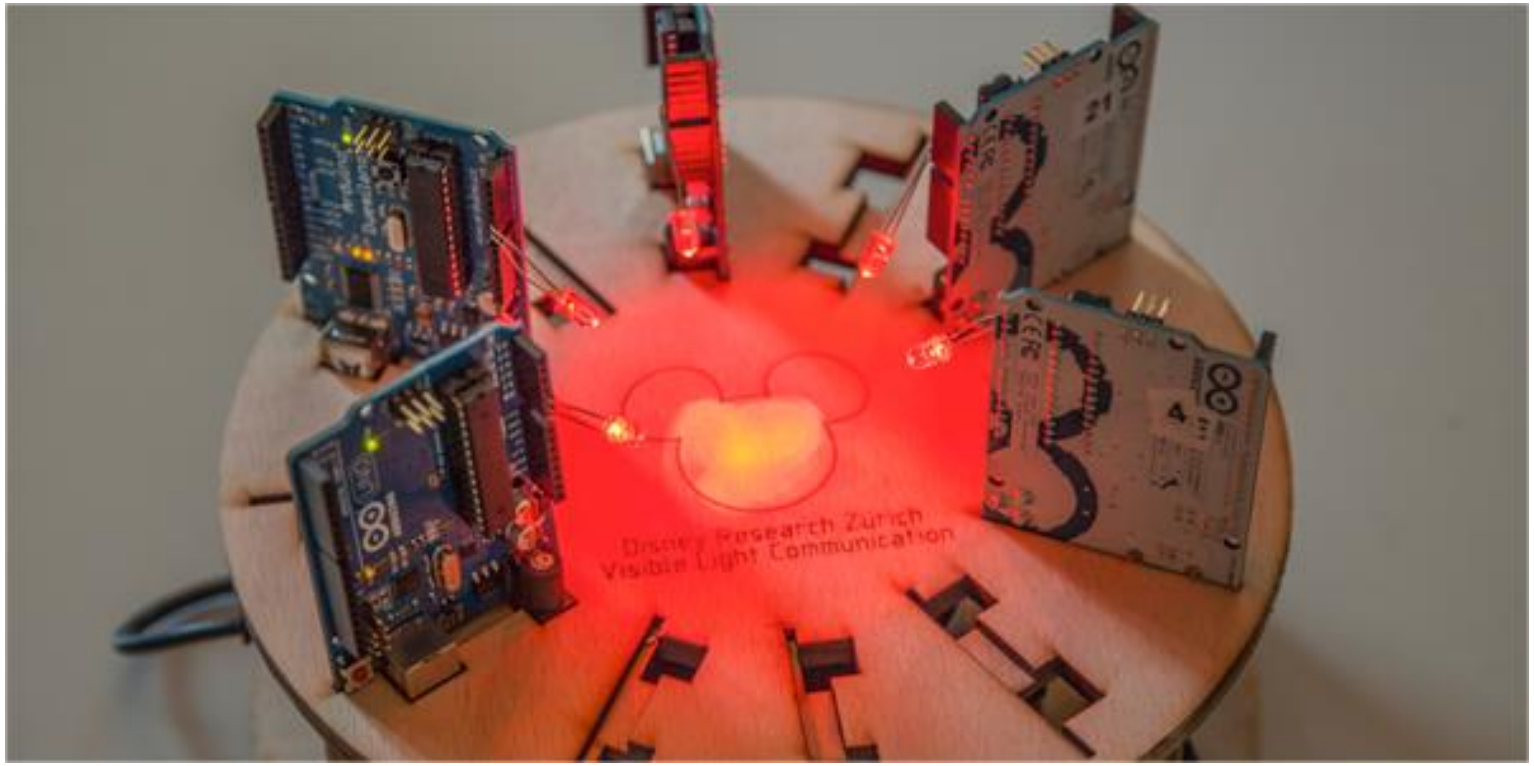
VLC Applications

- Indoor Positioning



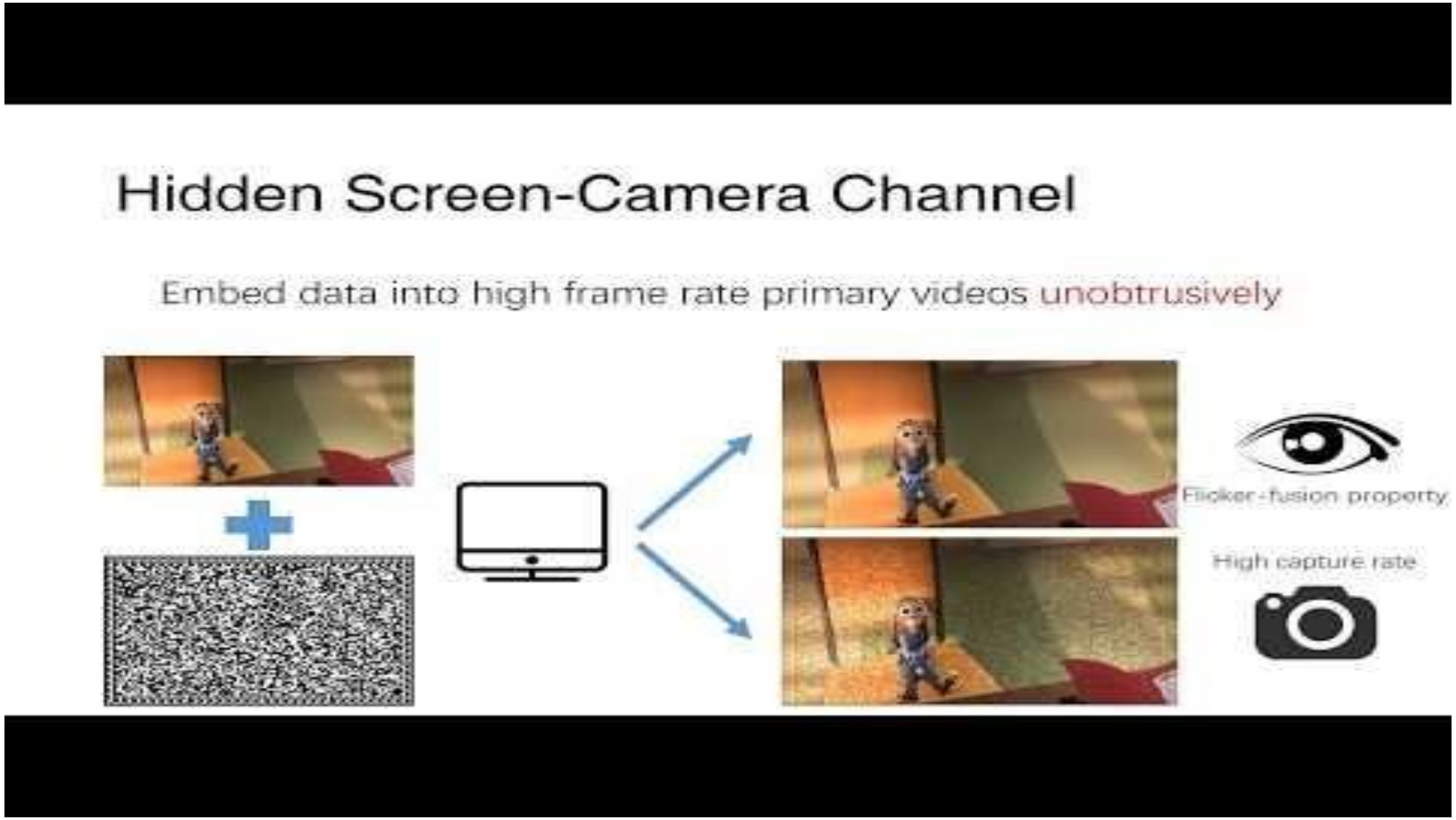
Other Schemes

- LED-to-LED communications



Other Schemes

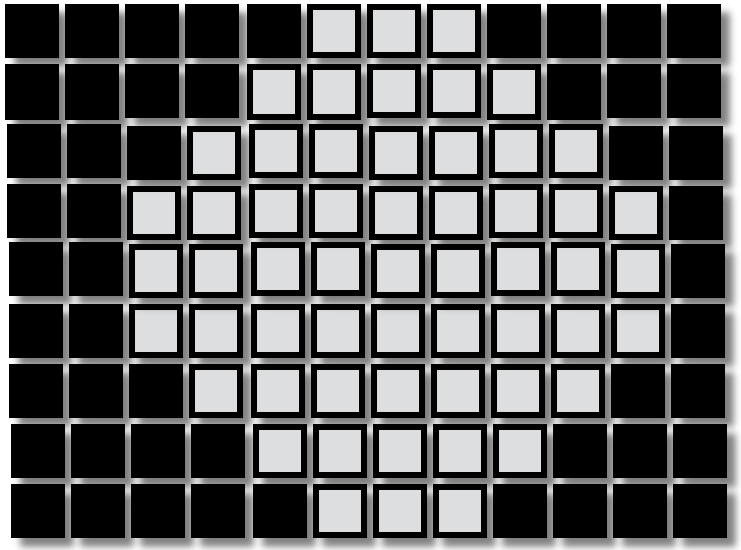
- Screen-to-camera communications
- https://youtu.be/WmkyRoM4Ja4



Other Schemes

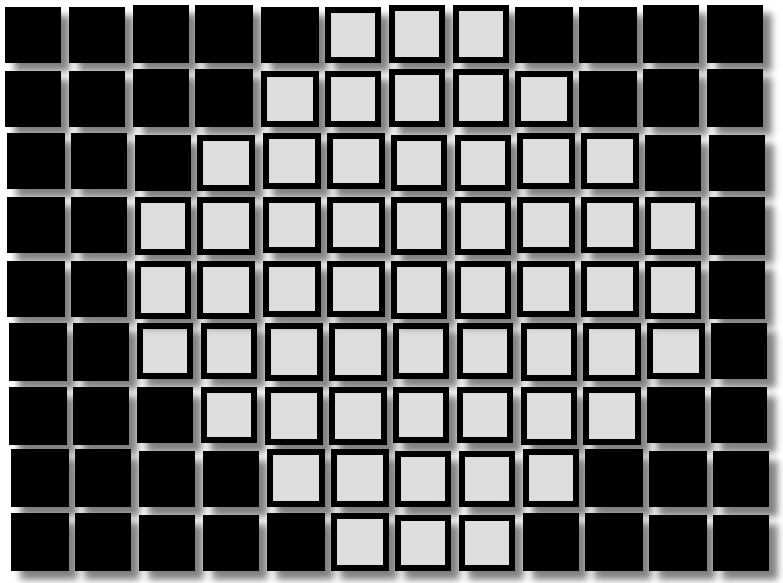
- Smartphone-based

Global Shutter



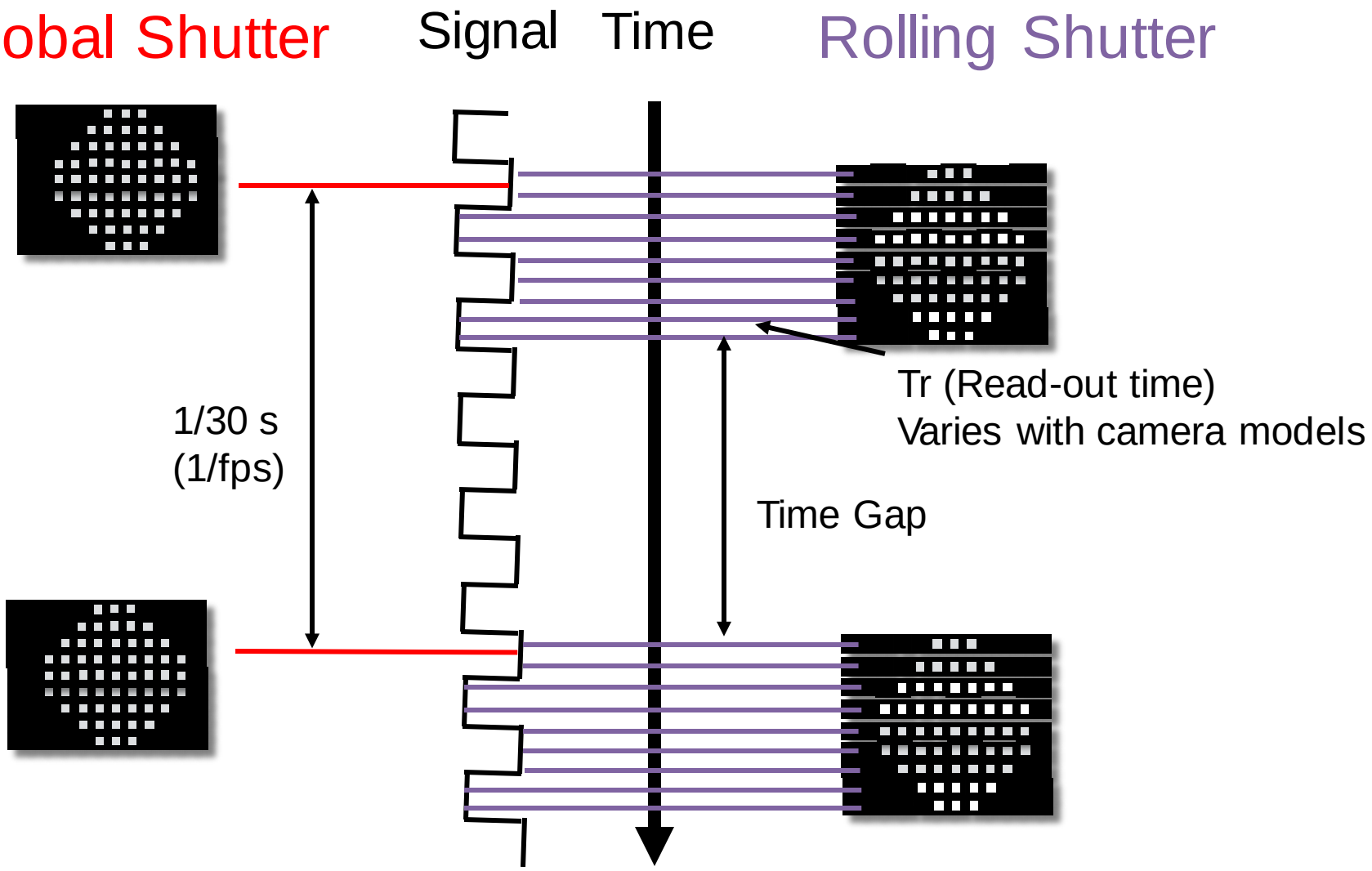
Pixels exposed
SIMULTANEOUSLY

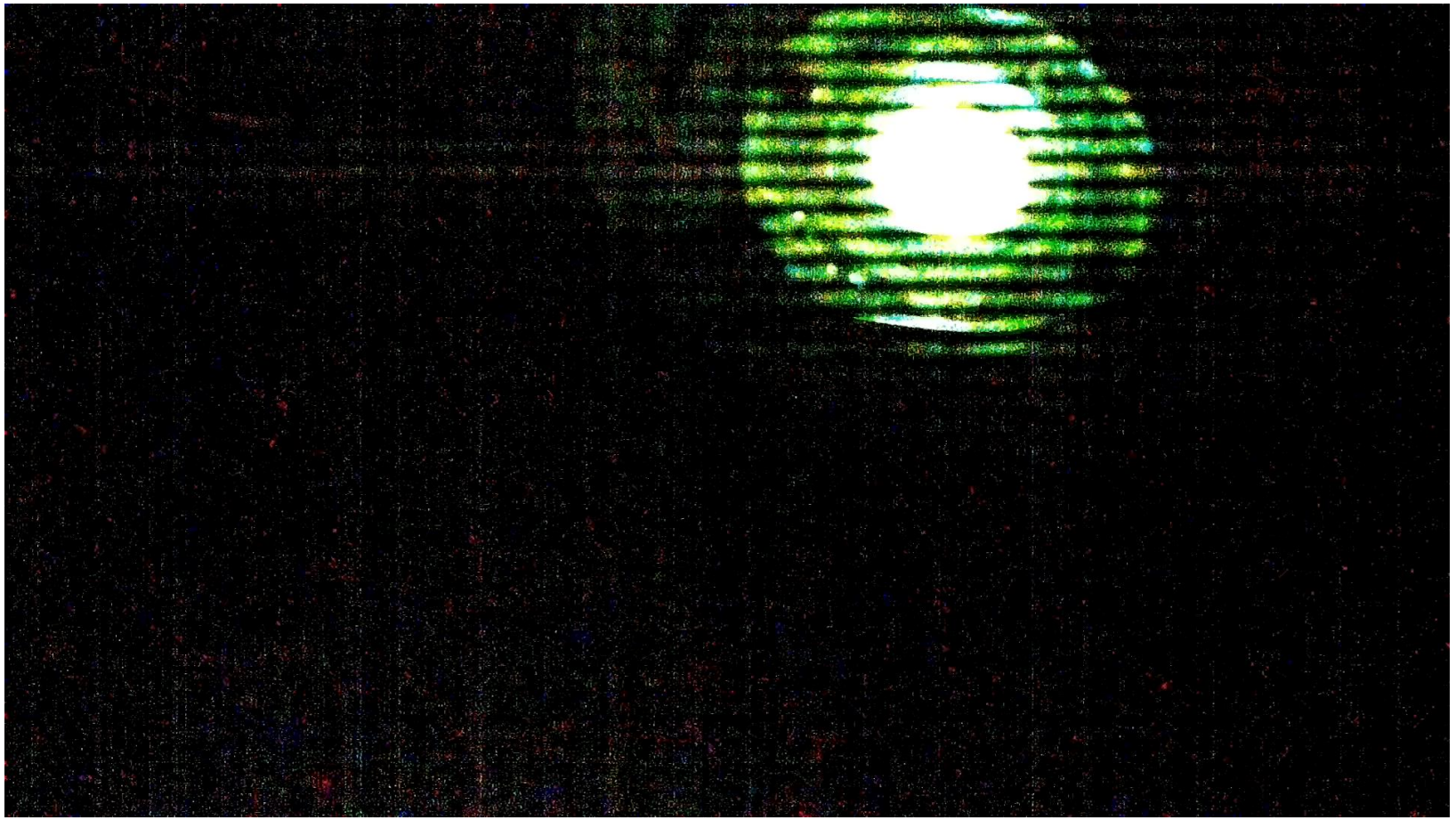
Rolling Shutter



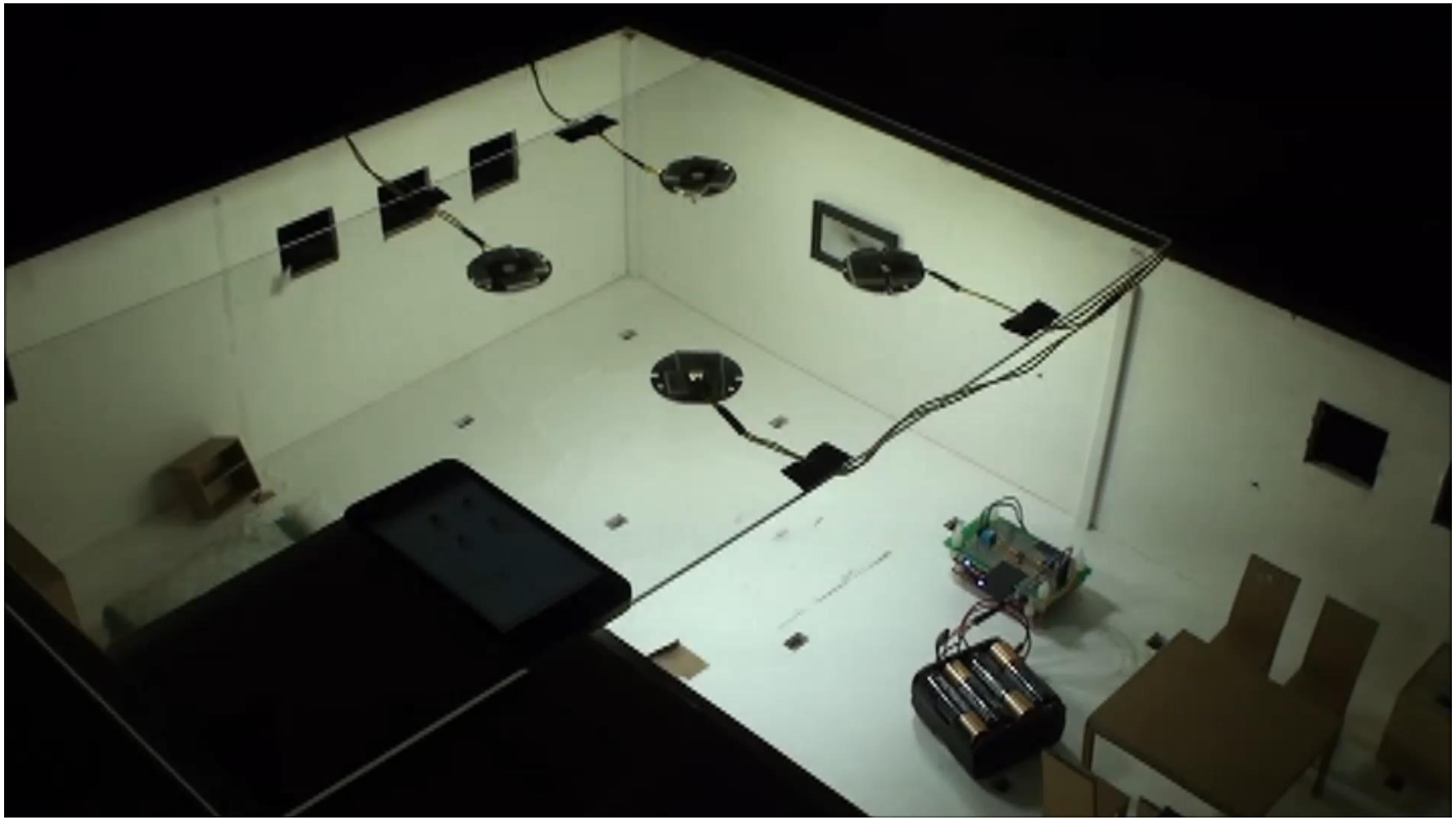
Pixels exposed
ROW BY ROW

How rolling shutter works ?





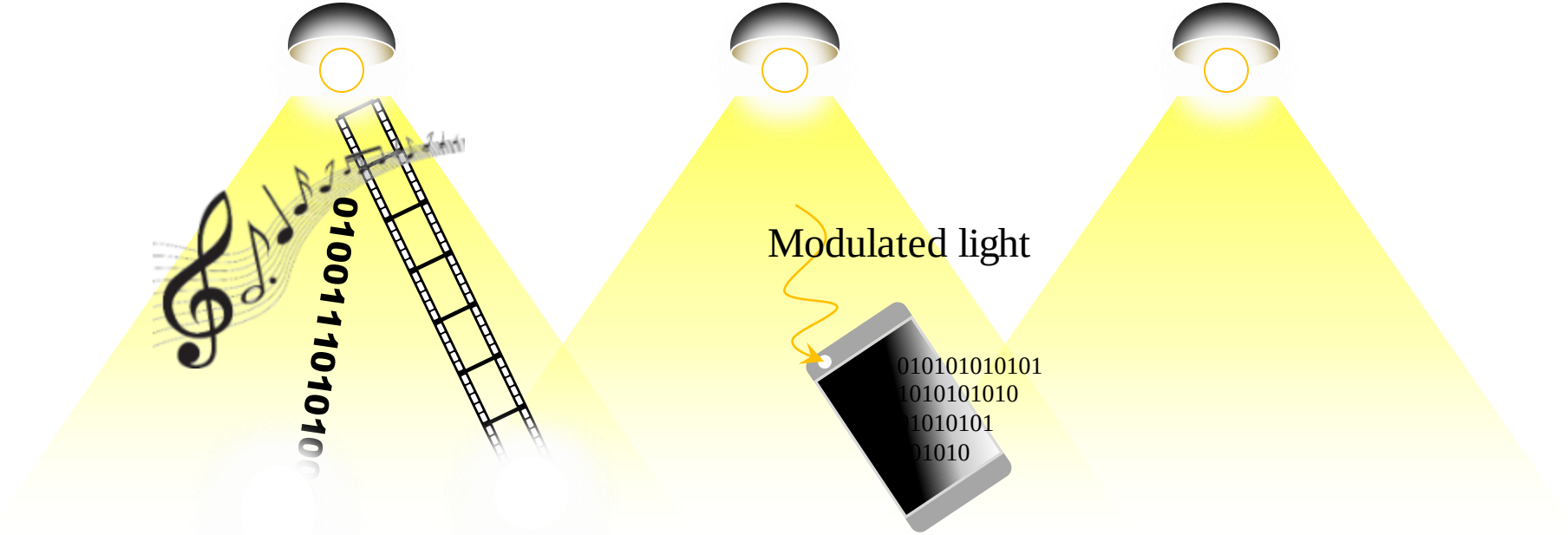
VLC LBS & Broadcasting System



INTRODUCTION

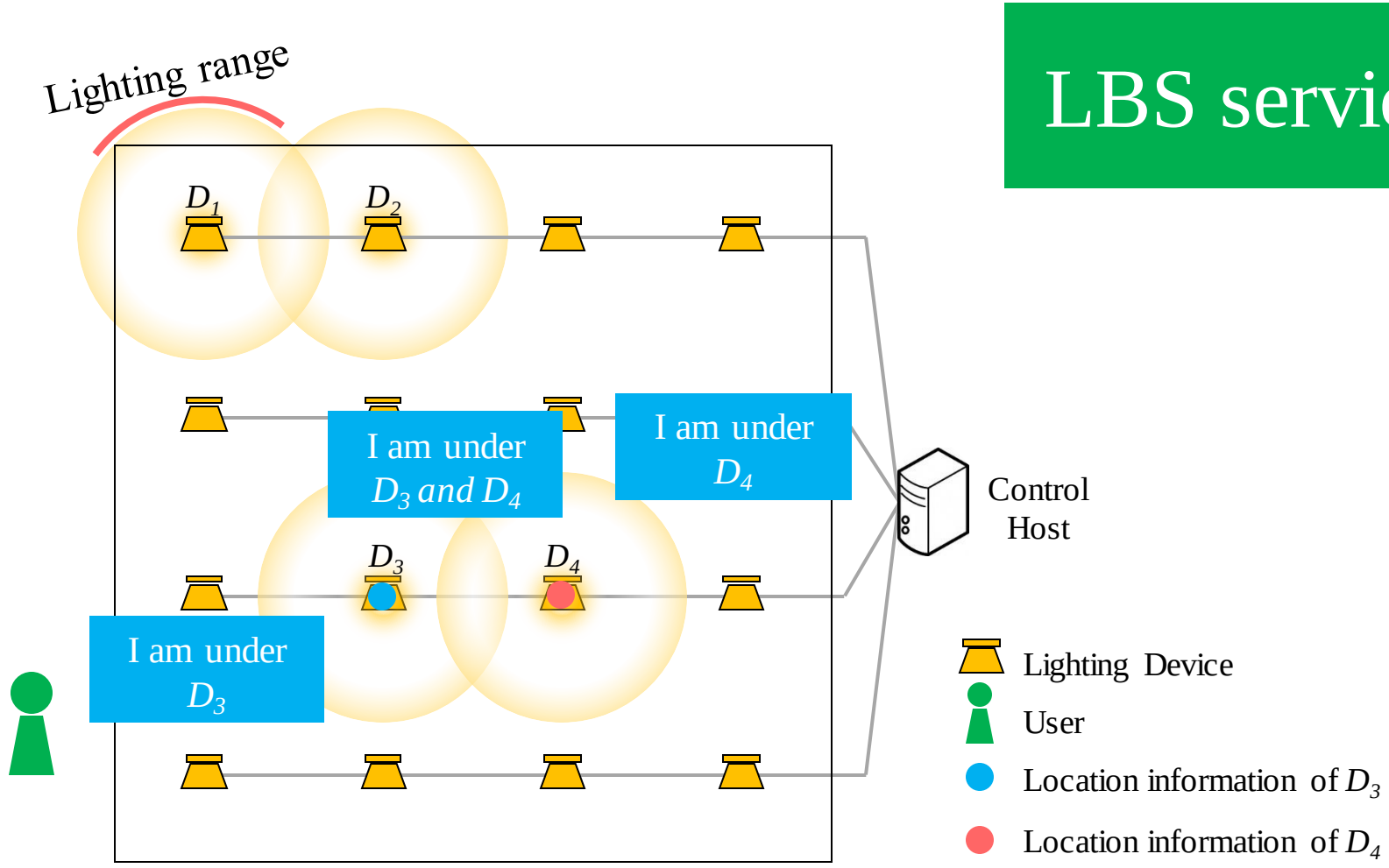
GOAL

- Construct an indoor *Visible Light Communication* system to provide essential information for applications through broadcasting
  - Utilize devices with LEDs to transmit information
  - Utilize devices with Photodiode to receive information



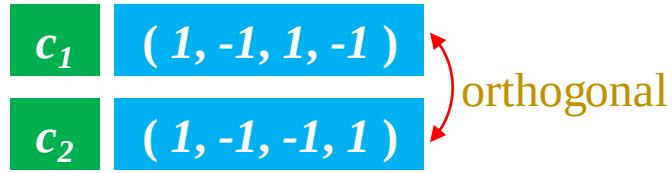
INTRODUCTION

GOAL



CDMA BASICS

- CDMA is a well-known spread spectrum technique in radio communications
  - Interference Avoidance
  - Sources are allowed to simultaneously send data over a common channel
  - Each source is assigned a unique code
    - The code is different from source to source
    - All codes are orthogonal



$$(1,-1,1,-1)\cdot(1,-1,-1,1)=0$$

  - Receivers will receive the multiplexed signal of multiple sources
    - Individual data can be extracted by computing inner product of the code c_i and the received signal

CDMA BASICS

- Given any two different codes c_i and c_j, the following orthogonal properties must hold:

$$c_i \cdot c_j = 0 \qquad c_i \cdot \bar{c}_j = 0$$

$\tilde{c}_j$ means c_j or $\bar{c}_j$

Guarantee any two codes will not interfere each other

If data bit = '1', using $\bar{c}_i$.

$$c_i \cdot x$$
$$= c_i \cdot (\tilde{c}_i + \cdots + \tilde{c}_{i-1} + c_i + \tilde{c}_{i+1} + \cdots + \tilde{c}_n)$$
$$= c_i \cdot \tilde{c}_i + \cdots + c_i \cdot \tilde{c}_{i-1} + c_i \cdot c_i + c_i \cdot \tilde{c}_{i+1} + \cdots + c_i \cdot \tilde{c}_n$$
$$= 0 + \cdots + c_i \cdot c_i + \cdots + 0$$
$$= \|c_i\|^2$$

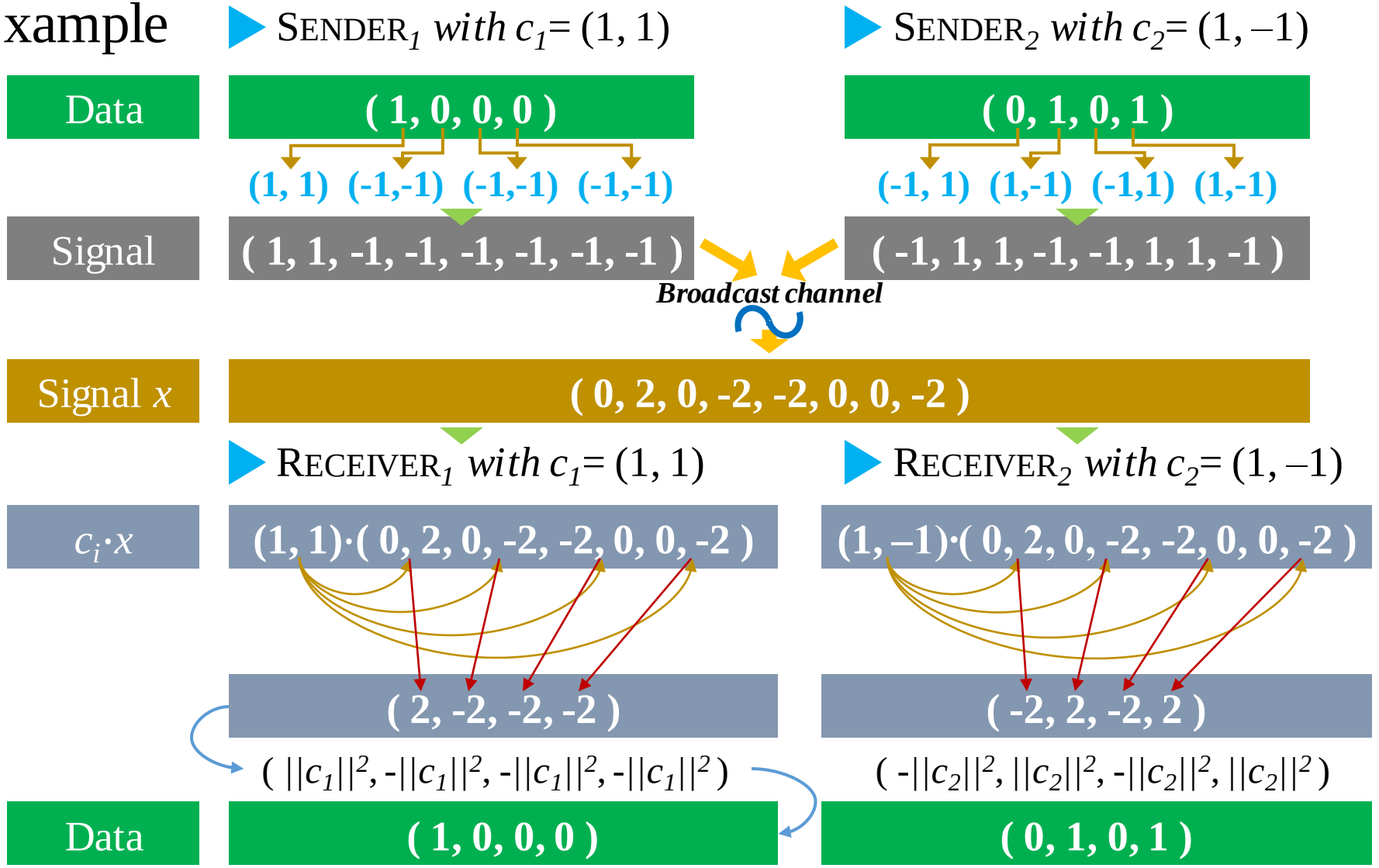
Property ①&②

If data bit = '0', using $\bar{c}_i$.

$$c_i \cdot x$$
$$= c_i \cdot (\tilde{c}_i + \cdots + \tilde{c}_{i-1} + \bar{c}_i + \tilde{c}_{i+1} + \cdots + \tilde{c}_n)$$
$$= c_i \cdot \tilde{c}_i + \cdots + c_i \cdot \tilde{c}_{i-1} + c_i \cdot \bar{c}_i + c_i \cdot \tilde{c}_{i+1} + \cdots + c_i \cdot \tilde{c}_n$$
$$= 0 + \cdots + c_i \cdot \bar{c}_i + \cdots + 0$$
$$= -\|c_i\|^2$$

CDMA BASICS

- Example



INTRODUCTION

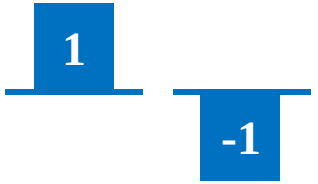
OBSERVATION

- Although CDMA is suitable for radio communications
  - It cannot be directly applied to VLC
    - Code in CDMA is a sequence of '1's and '−1's

c_1	(1, -1, 1, -1)
c_2	(1, -1, -1, 1)

    - CDMA is designed for bipolar systems

BIPOLAR SYSTEMS



- In VLC, we need to use 'light on' and 'light off' to distinguish data.
  - The generated signal is unipolar
    - No negative components ('-1's)

UNIPOLAR SYSTEMS

INTRODUCTION

OBSERVATION

- Drawbacks without negative components
  - Orthogonal properties

		VLC
c_1	(1, 1)	(1, 1)
$\overline{c_1}$	(-1, -1)	(0, 0)
c_2	(1, -1)	(1, 0)
$\overline{c_2}$	(-1, 1)	(0, 1)

$c_i \cdot c_j = 0$

Any two codes will interfere with each other

$c_1 \cdot c_2 = (1, 1) \cdot (1, 0) \neq 0$

$c_i \cdot c_i = \|c_i\|^2$

Transmit of bit '1' is unaffected

$c_1 \cdot c_1 = (1, 1) \cdot (1, 1) = 2$

$c_i \cdot \overline{c_i} = -\|c_i\|^2$

The role of $\overline{c_i}$ cannot be correctly defined

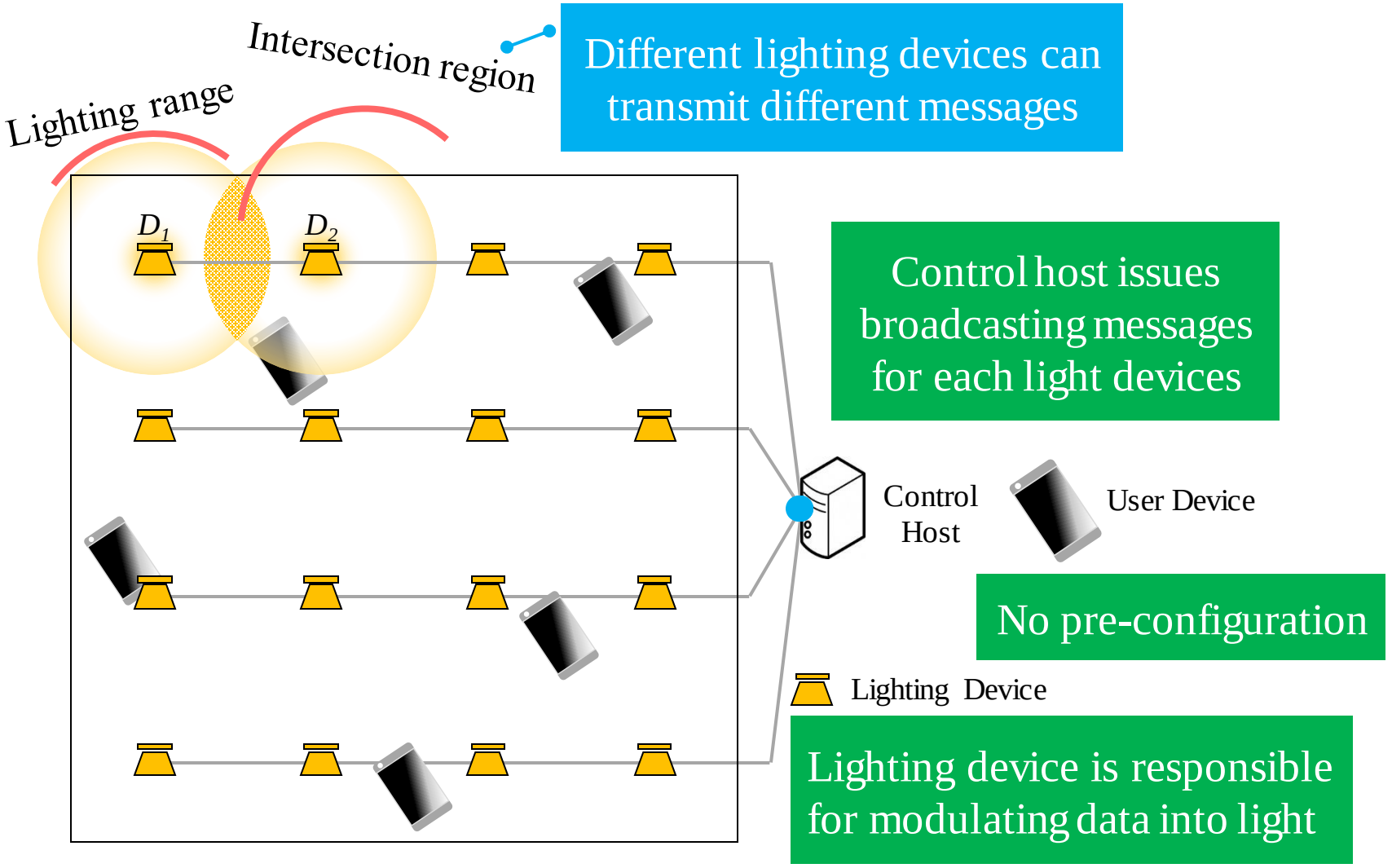
$c_1 \cdot \overline{c_1} = (1, 1) \cdot (0, 0) \neq -2$

Lack of bit '0'

CONTRIBUTION

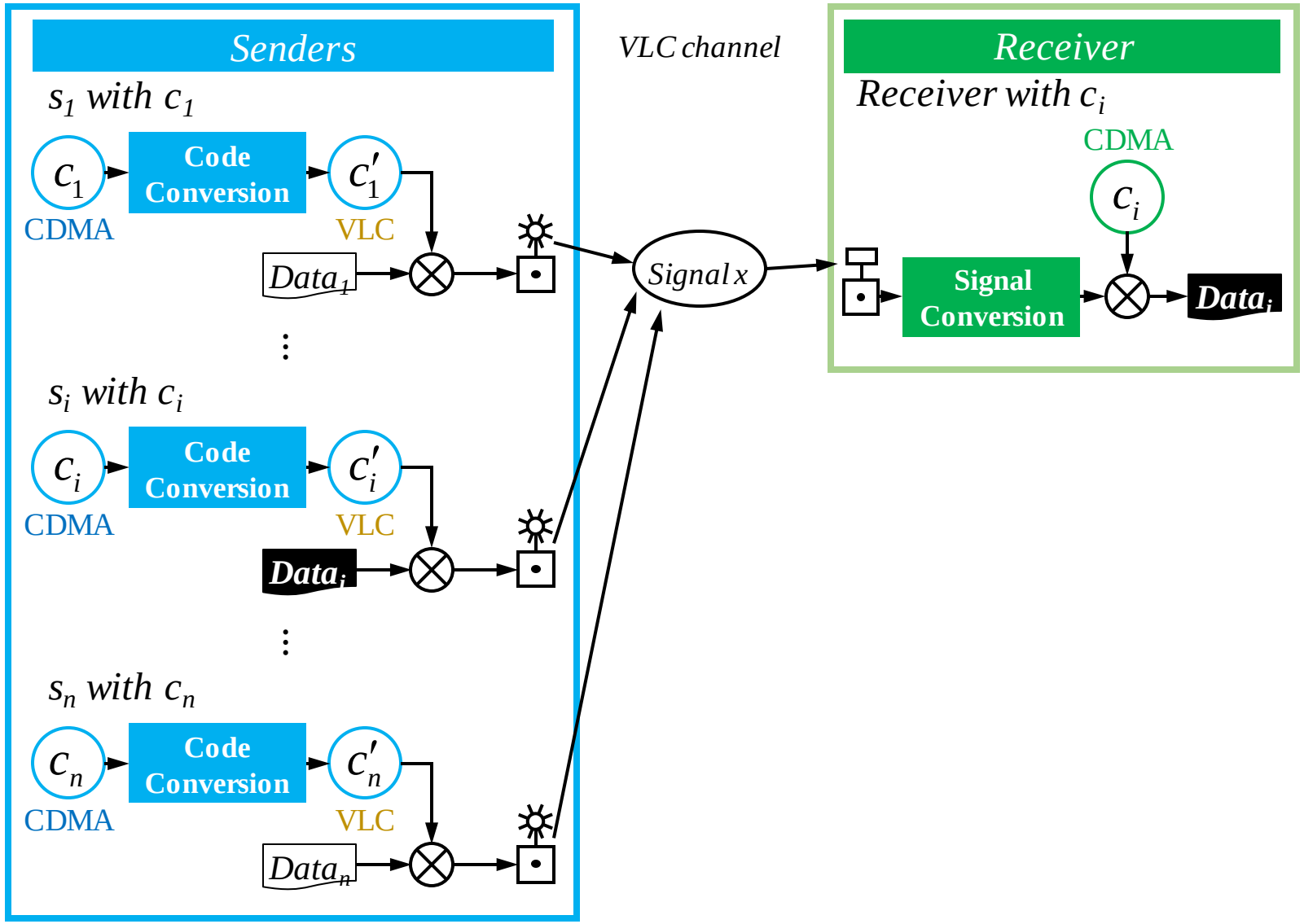
- Propose a CDMA-based message broadcasting system to deal with the interference problem in indoor VLC
  - Deal with multi-source interference
  - A Modified CDMA encoding and decoding schemes are proposed to adapt unipolar systems
  - A broadcasting frame structure is designed to realize our system
- Our system can support various types of applications, which need unidirectional messages.
- Prototyping

System Architecture

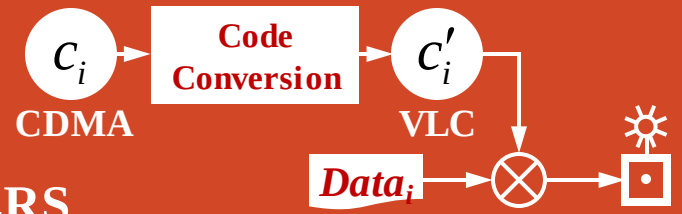


System Design

Modified CDMA Flow Chart



System Design



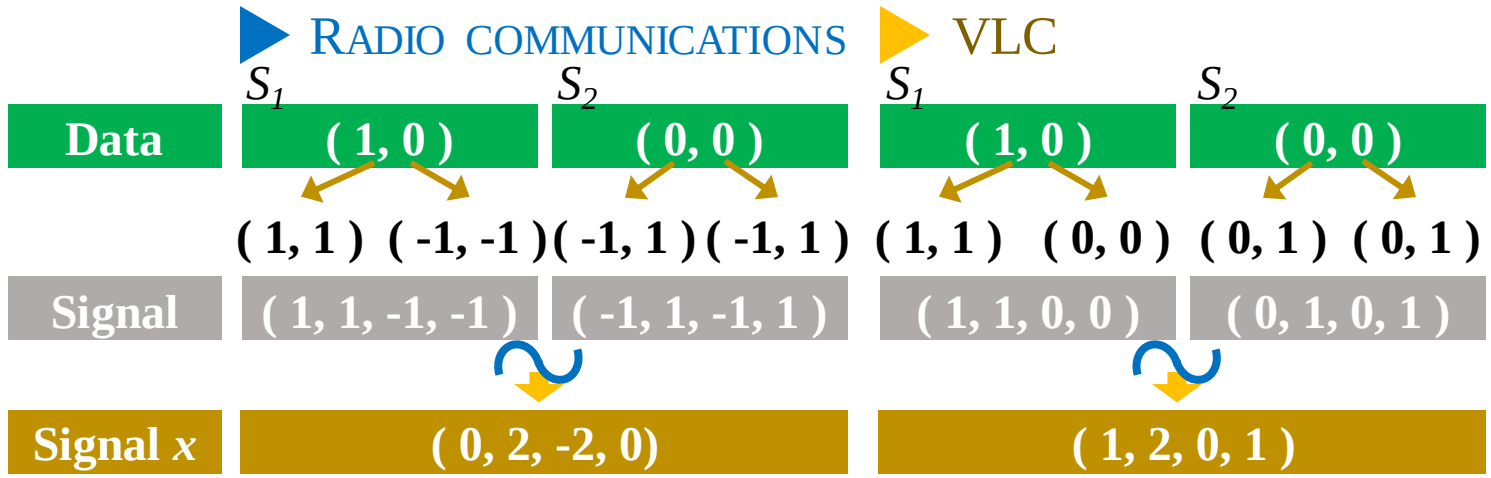
Senders

- Convert code c_i to c'_i by replacing each '-1' in c_i by '0'
  - Introduces the unipolar property to VLC

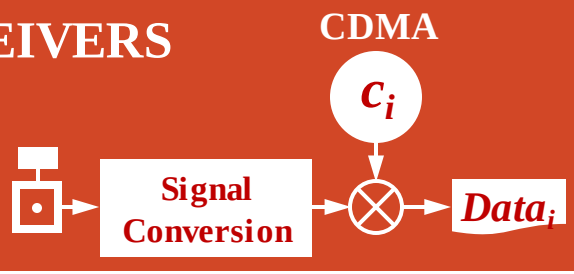
	Radio	VLC	
c_1	(1, 1)	(1, 1)	c'_1
$\overline{c_1}$	(-1, -1)	(0, 0)	$\overline{c'_1}$
c_2	(1, -1)	(1, 0)	c'_2
$\overline{c_2}$	(-1, 1)	(0, 1)	$\overline{c'_2}$

S_1 with code c_1
S_2 with code c_2

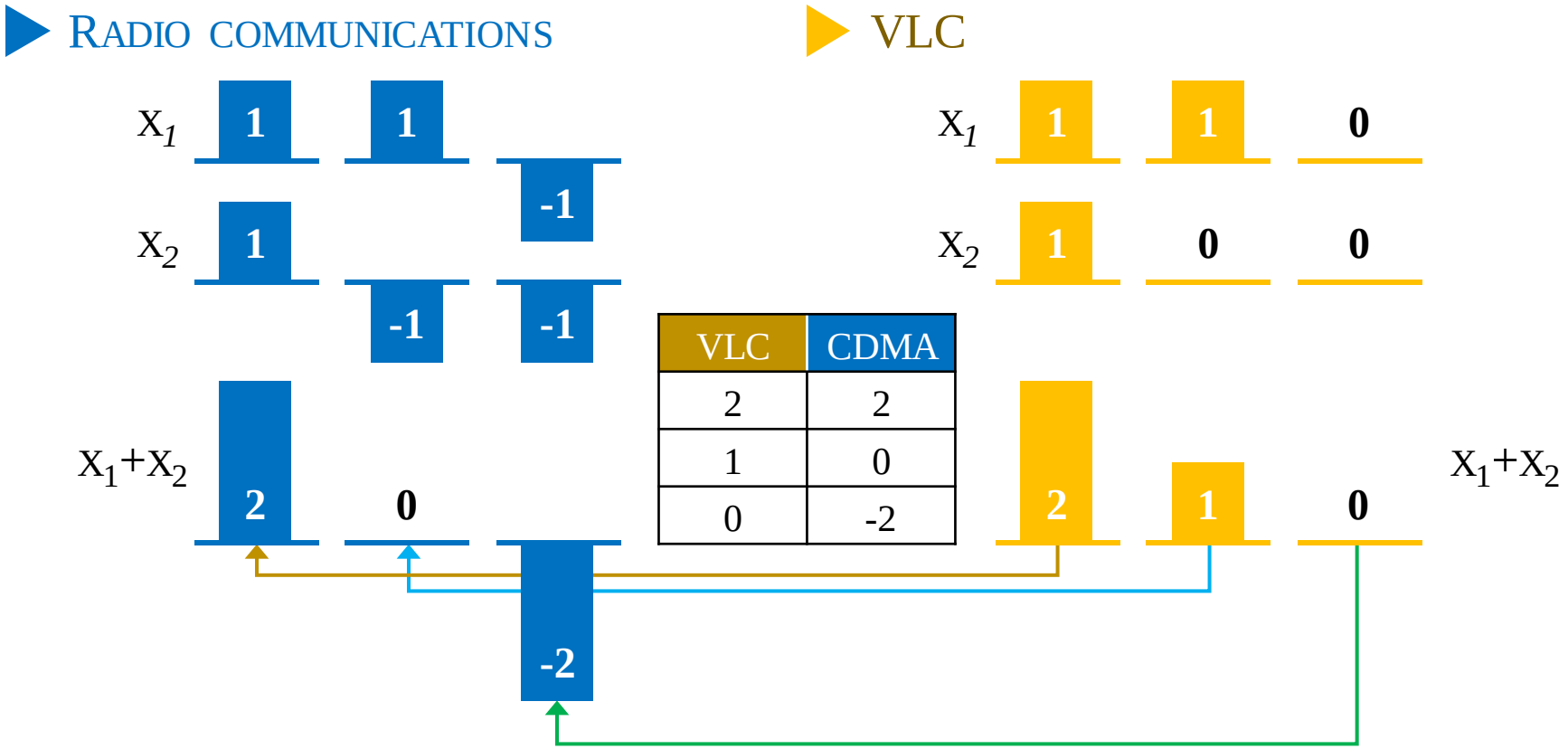
S_1 with code c'_1
S_2 with code c'_2



System Design

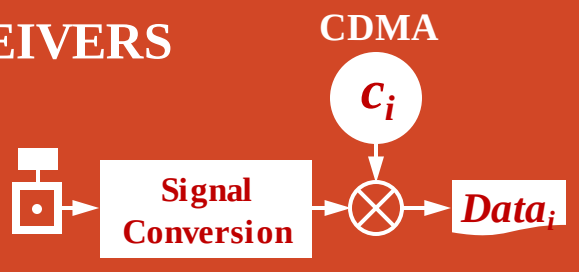


- Observation
  - VLC signals could be transformed to the bipolar system.



System Design

Receivers



- Three sources and four sources

Combination

x_1	1	0	0	0
x_2	1	1	0	0
x_3	1	1	1	0
sig →	3	2	1	0

s_1	1	-1	-1	-1
s_2	1	1	-1	-1
s_3	1	1	1	-1
	3	1	-1	-3

FOR THREE SOURCES

$1=(1)\times 1+(0)\times(4-1)$

Combination

x_1	1	0	0	0	0
x_2	1	1	0	0	0
x_3	1	1	1	0	0
x_4	1	1	1	1	0
sig →	4	3	2	1	0

FOR FOUR SOURCES

$(1)\times 1+(-1)\times(4-1)=-2$

x_1	1	-1	-1	-1	-1
x_2	1	1	-1	-1	-1
x_3	1	1	1	-1	-1
x_4	1	1	1	1	-1
	4	2	0	-2	-4

System Design

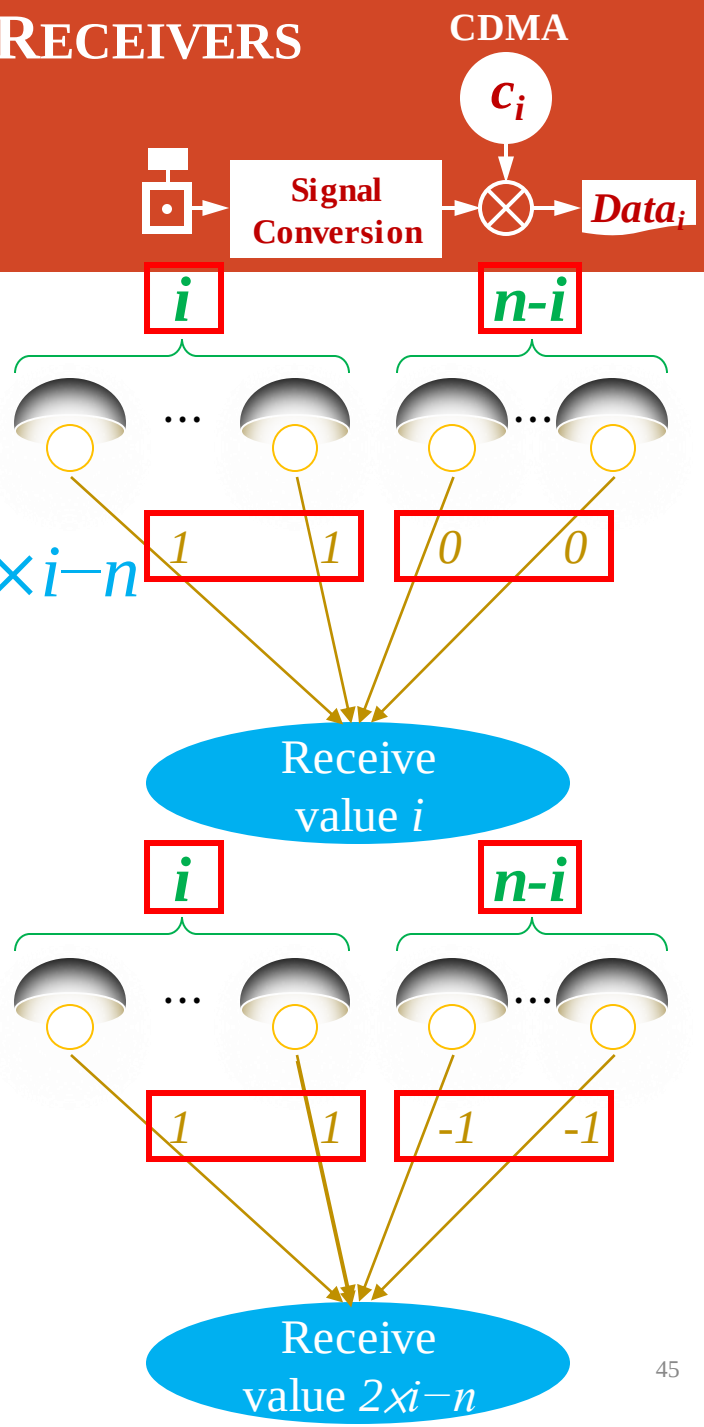
Receivers

- Generic transformation method
  - Works for any n sources
- Transform each signal i in VLC to $2\times i-n$
  - i '1's and $(n-i)$ '0's in VLC

$$\rightarrow i\cdot(1)+(n-i)\cdot(0)=i$$

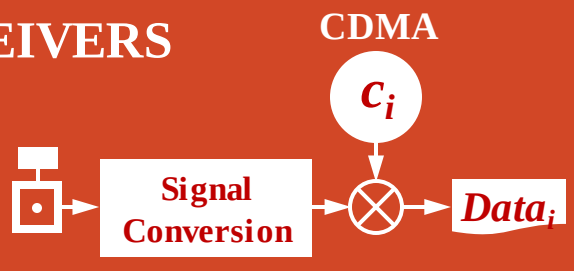
  - i '1's and $(n-i)$ '-1's in CDMA

$$\rightarrow i\cdot(1)+(n-i)\cdot(-1)=2\times i-n$$



System Design

Receivers



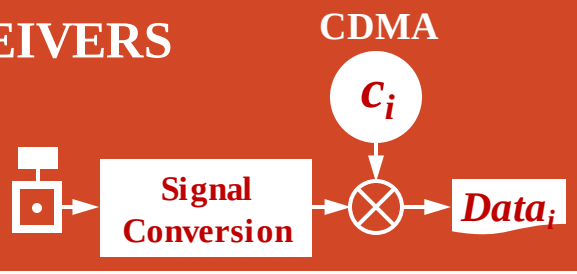
- Mapping the element *i* in VLC to a element in CDMA

VLC		CDMA
0	→	*-n*
1	→	*-n+2*
2	→	*-n+4*
…		…
i	→	*2i - n*
…		…
n	→	n

$$i = f(i) = (i)\times(1)+(n-i)\times(-1) = 2i-n$$

$$i\times 1+(n-i)\times 0$$

System Design



- Example
  - 3 sources
  - Received signal sequence (*0, 1, 3, 1*)

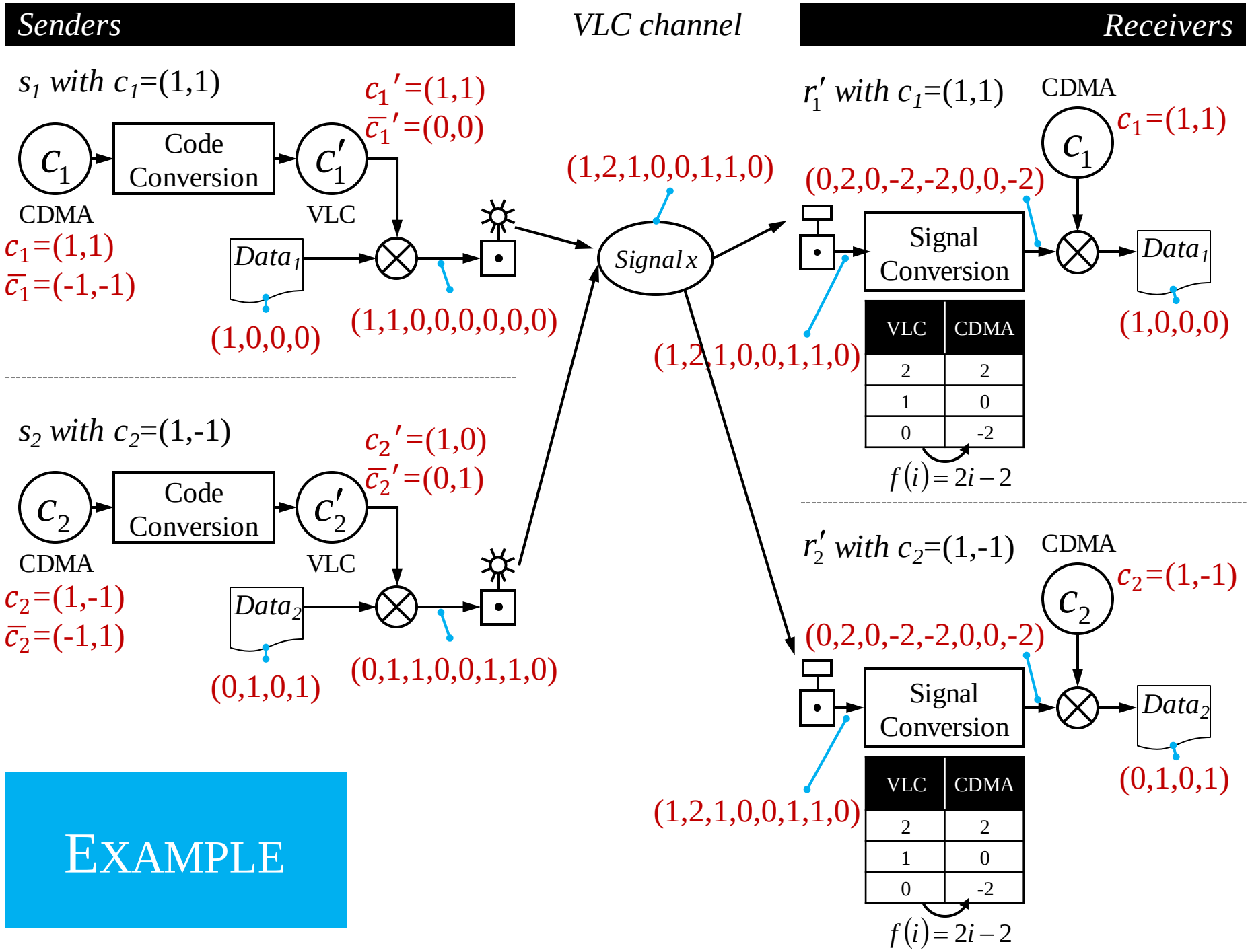
Sequence (0, 1, 3, 1) in VLC is related to sequence (-3, -1, 3, -1) in radio communications

$$f(i) = 2i - 3$$

VLC	Radio
0	-3
1	-1
2	1
3	3

Received: 0, 1, 3, 1

Transformed: -3, -1, 3, -1


Senders
VLC channel
Receivers
s_1 with c_1=(1,1)
c_1=(1,1)
$\bar{c}_1$=(-1,-1)
Code Conversion
CDMA
VLC
c_1'=(1,1)
$\bar{c}_1'$=(0,0)
Data1
(1,0,0,0)
(1,1,0,0,0,0,0,0)
s_2 with c_2=(1,-1)
c_2=(1,-1)
$\bar{c}_2$=(-1,1)
c_2'=(1,0)
$\bar{c}_2'$=(0,1)
Data2
(0,1,0,1)
(0,1,1,0,0,1,1,0)
(1,2,1,0,0,1,1,0)
Signal x
r_1' with c_1=(1,1)
(0,2,0,-2,-2,0,0,-2)
Signal Conversion
VLC
CDMA
2
2
1
0
0
-2
$f(i) = 2i - 2$
Data1
(1,0,0,0)
(1,2,1,0,0,1,1,0)
r_2' with c_2=(1,-1)
(0,2,0,-2,-2,0,0,-2)
Signal Conversion
VLC
CDMA
2
2
1
0
0
-2
$f(i) = 2i - 2$
Data2
(0,1,0,1)
(1,2,1,0,0,1,1,0)

EXAMPLE

System Design

Broadcasting frame structure design

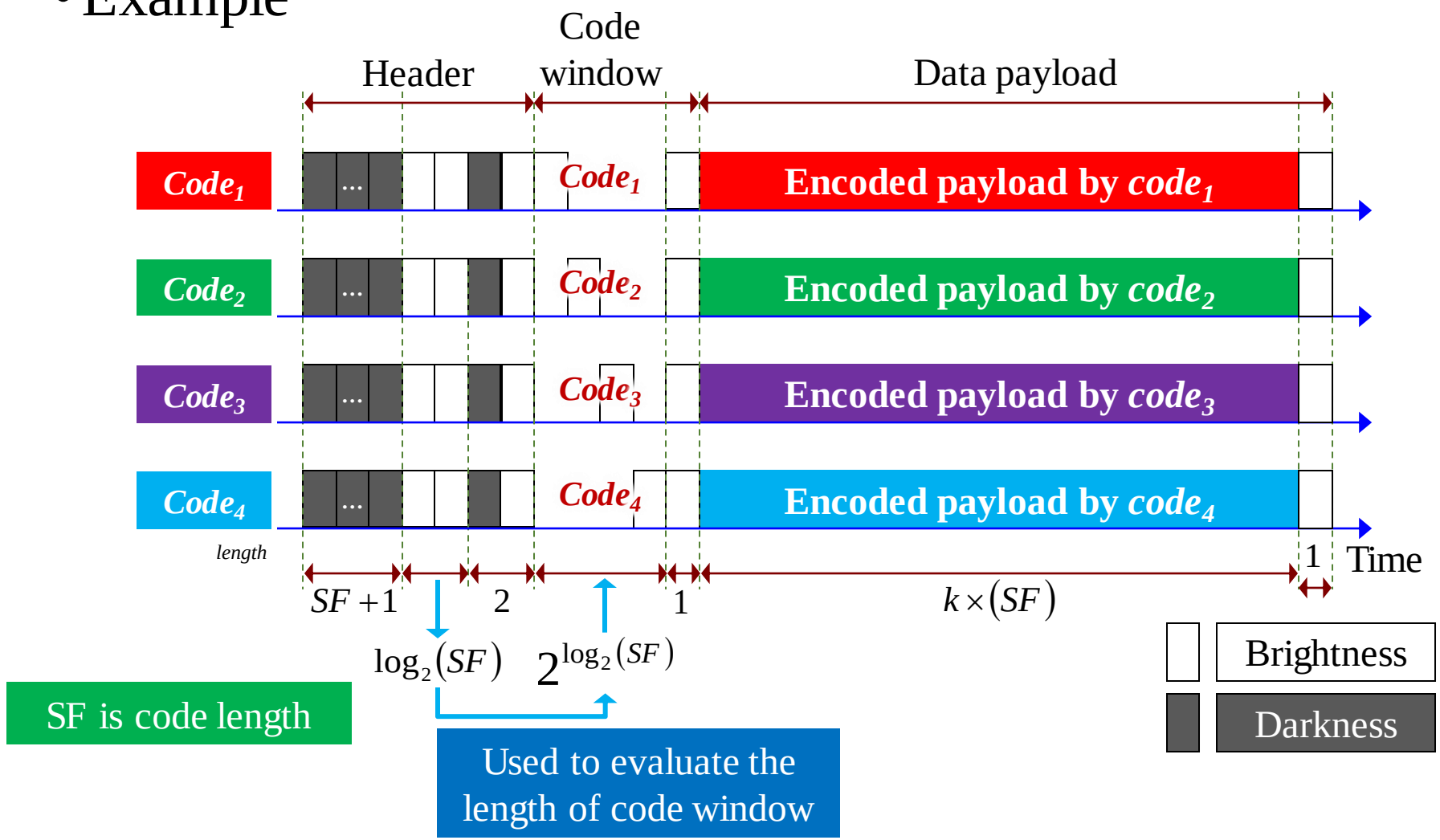
- In order to correctly transmit the information
  - A broadcasting frame structure design is proposed including
    - Header
      - Identify the beginning of a frame and code information for receiver
    - Code window
      - Notify receiver the core information -which codes are uesd
    - Data payload
      - Carry the main message, which is encoded by the CDMA encoding scheme.

Frame format

System Design

Broadcasting frame structure design

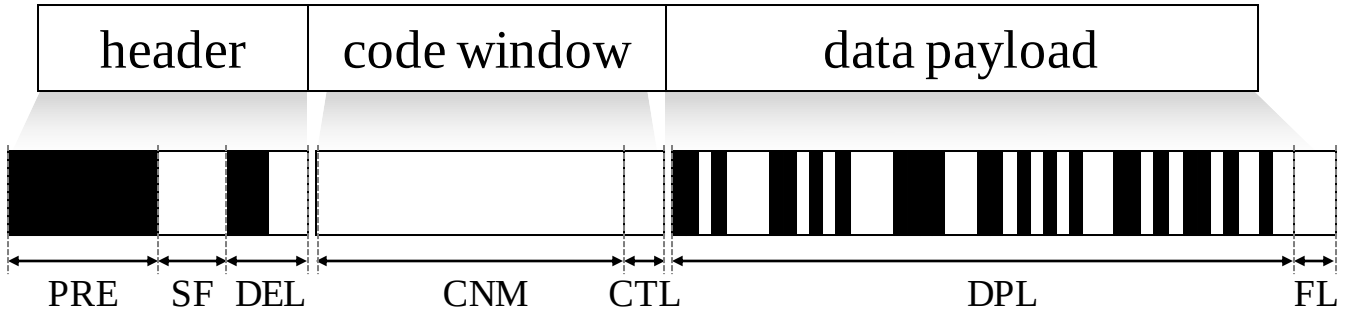
- Example



System Design

Broadcasting frame structure design

- In order to correctly transmit the information
  - An unanimous frame structure design is proposed including
    - Header
    - Code window
    - Data payload

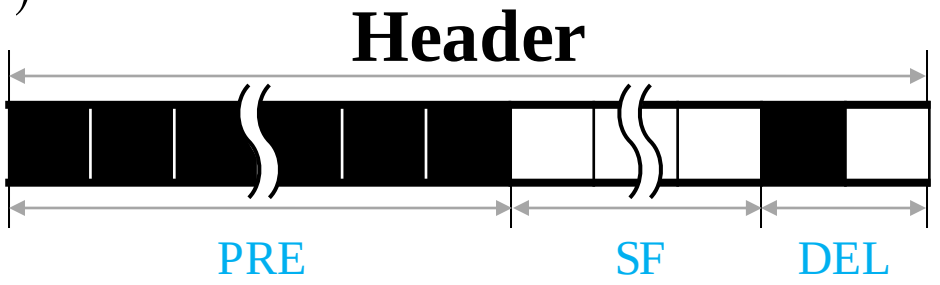


PRE	:	Preamble
SF	:	Spreading Factor
DEL	:	Delimiter
CNM	:	Code Notification Map
CTL	:	Code window Trailer
DPL	:	Data Payload
FL	:	Frame Trailer

BROADCASTING FRAME STRUCTURE DESIGN

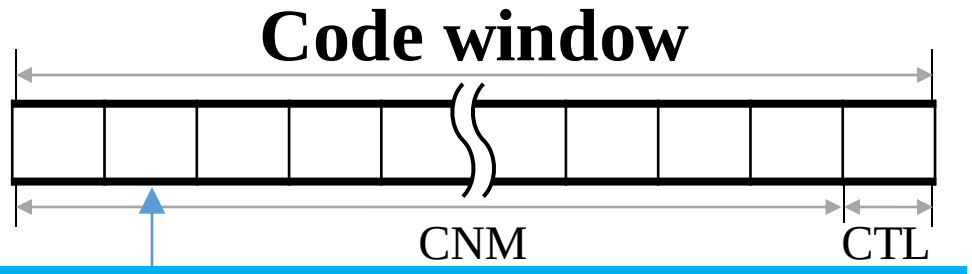
- Header
  - Preamble (PRE)
    - Appearance at the beginning of a frame
    - Continuous darkness
  - Spreading Factor (SF)
    - Indicate receiver the *spreading factor (SF)* number
    - The size of SFI $N_{SFI} = \log_2(SF)$
    - Continuous brightness
  - Delimiter (DEL)
    - The end of a header
    - 1 darkness & 1 brightness

Spread factor is the ratio of chip rate to bit rate



BROADCASTING FRAME STRUCTURE DESIGN

- Code window
  - Find the CDMA codes being used by the transmitters
  - Number of orthogonal codes
    - Used by signal conversion
  - The size of CNM is $N_{CNM} = 2^{N_{SFI}}$



If source adopts second code, it sets second slot to brightness and sets the remaining slots to darkness.

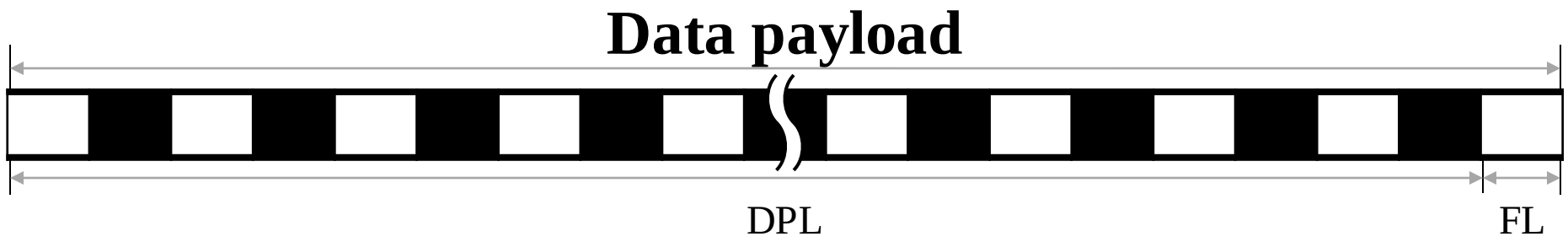
If the *i-th* slot is brightness, it means the *i-th* code is adopted.

Otherwise, if the *i-th* slot is darkness, it means the *i-th* code is unadopted.

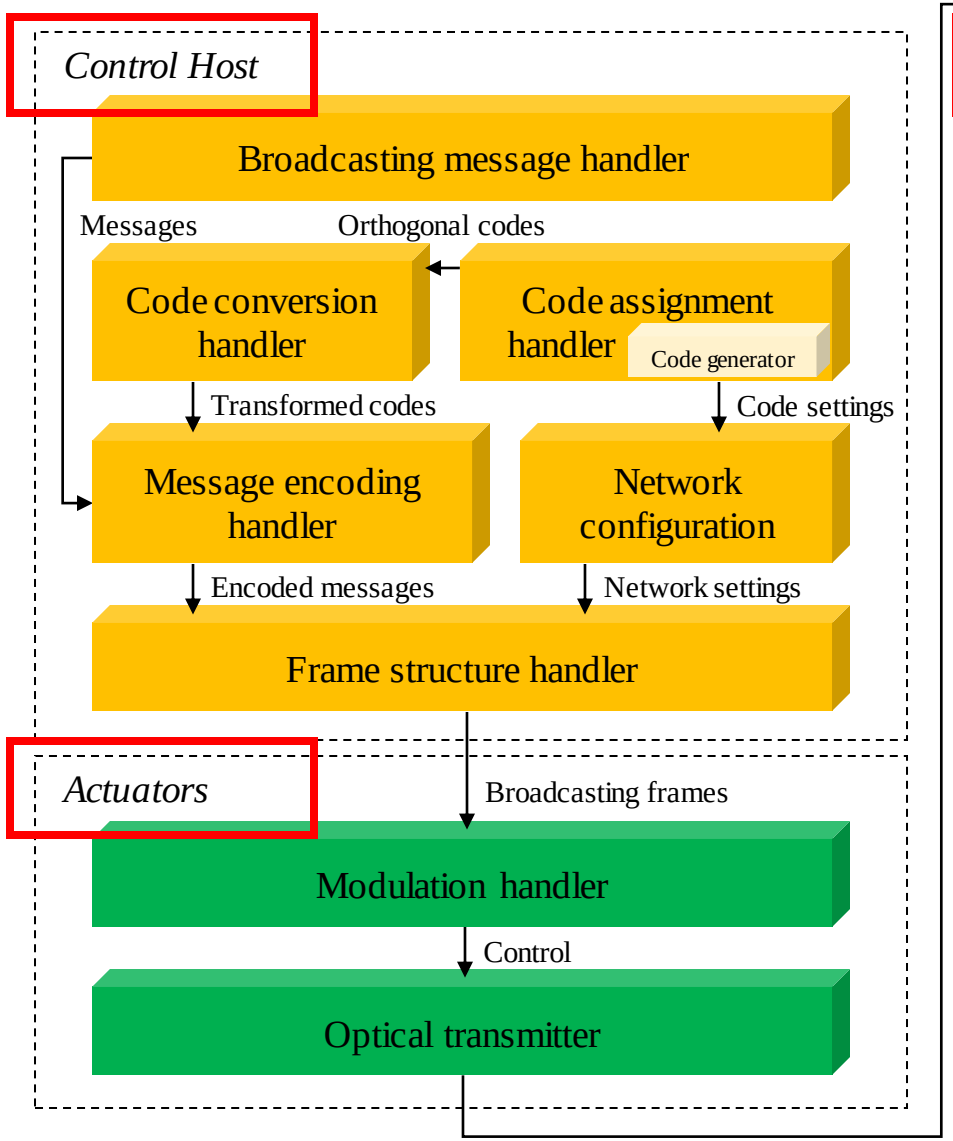
BROADCASTING FRAME STRUCTURE DESIGN

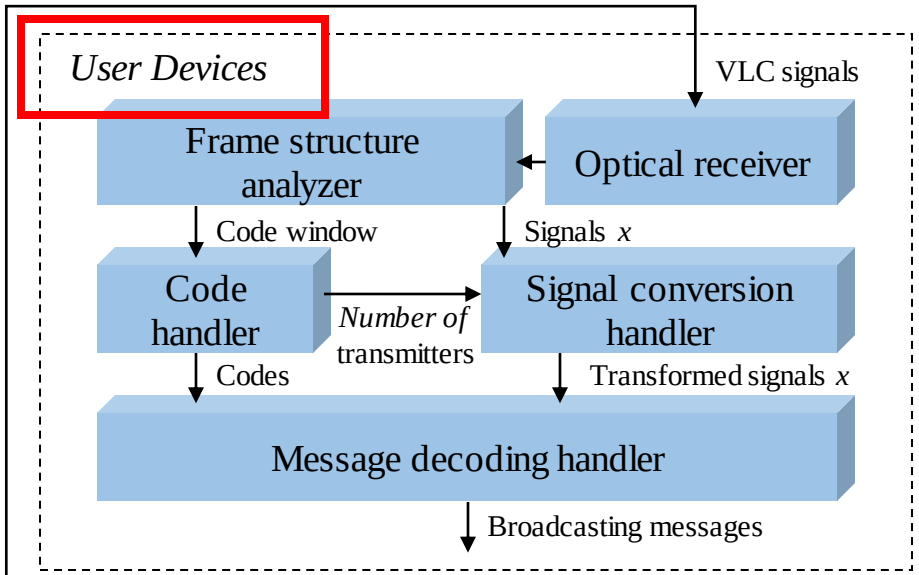
- Data payload
  - Carrying the actual data
  - Data is added into DPL after it has been encoded
    - Through normal CDMA encoding process
  - The size of DPL must satisfy

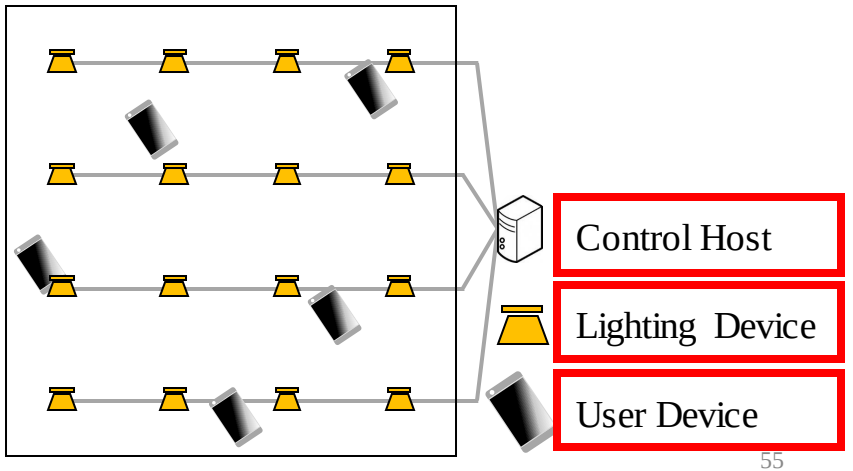
$$N_{DPL} \equiv 0 \left(\mathrm{mod}\ SF\right)$$



PROTOTYPING RESULTS







PROTOTYPING RESULTS

User Devices