# Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

**Submission Title:** Proposal for OWC Using Color Space Modulation
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**Re:** CFP of 15.7r1

**Abstract:** Proposal for OWC for low rate and high rate communications

**Purpose:** to submit a proposal for 802.15.7r1

# COLOR SPACE MODULATION PROPOSED

# CONSIDERATIONS FOR MODULATION

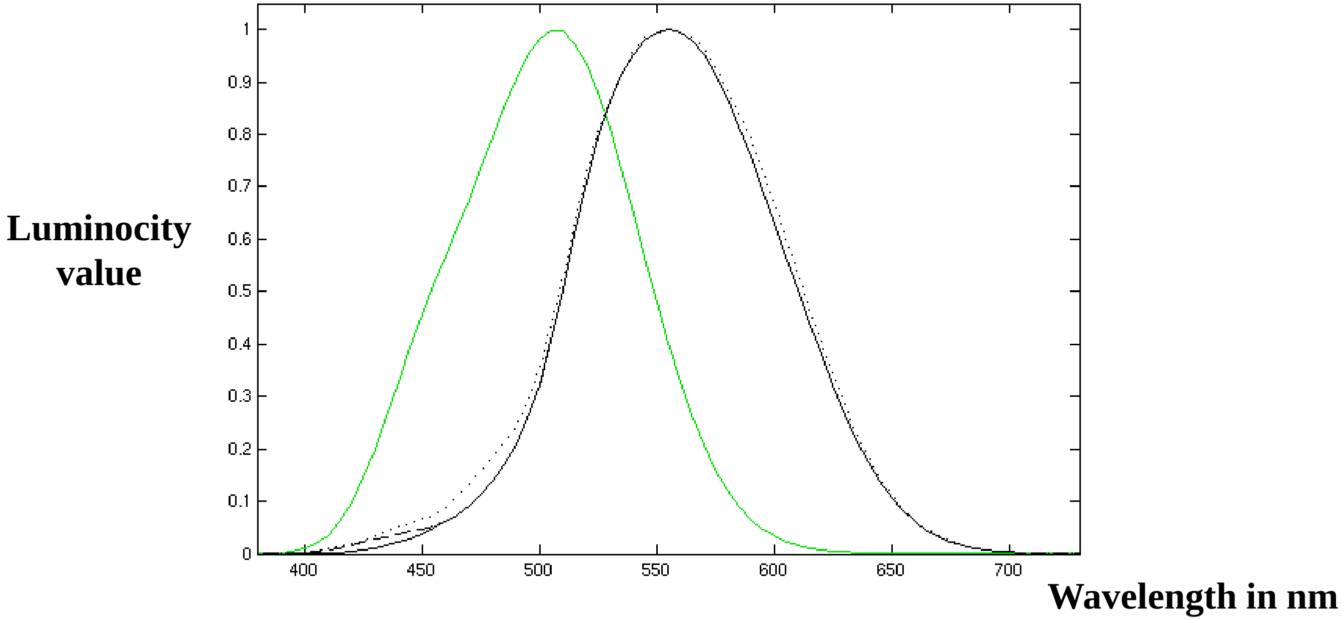
- Need of brightness control or not
  - Need superior brightness for optical wireless communications?
  - It is more desirable for performance not to be affected by brightness control.
- Dependency of light source characteristics
  - Is a modulation technique applied not dependent on technical characteristics of LEDs or other light sources deployed?
- Not (or negligibly) affected by background noise or not
  - Offsetting the impact of background light sources
  - Stable data transmission should be achieved even if the background noise is strong.
  - Offers high robustness to background light
- Data speed
  - Low to high data rates to be realized: adaptive to the amount of information delivered
  - **Adaptiveness to various data rates is important.**

# MAJOR DISTINCTIONS BETWEEN OWC AND RADIO COMMUNICATION

| OWC | Radio comm. |
|---|---|
| Data delivery by manipulating and measuring light, in terms of its perceived **brightness or color:** light intensity, color, etc.<br><br>The radiant power at each wavelength is weighted by a luminosity function (a.k.a. visual sensitivity function) that models human brightness sensitivity. | Data delivery by manipulating electromagnetic signals and detecting parameters of the received signals or measuring radiant energy: amplitude, frequency, phase, etc. |
| A light signal which will be manipulated for data delivery has a certain amount of frequency (or wavelength) band before modulation. | A carrier signal usually has a single frequency component which is modulated with data. Eventually the transmitted signal has a certain amount of band after modulation. |

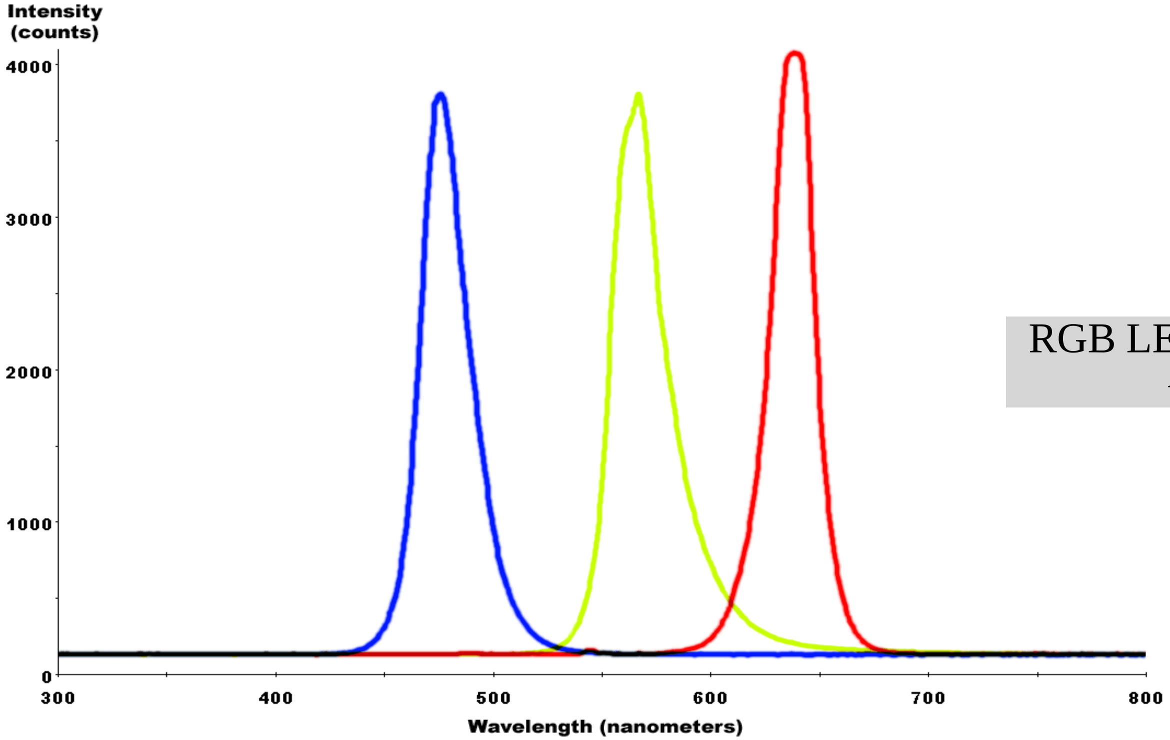
# FACTORS CONSIDERED FOR OWC MODULATION (1)

- Eye sensitivity
  - To generate light with a color which is recognized by human eyes
  - Human eyes have different sensitivity for each wavelength: **luminocity functions** reflect human eyes' sensitivity for various wavelengths.
  - To determine colors recognized by human eyes after modulation



# FACTORS CONSIDERED FOR OWC MODULATION (2)

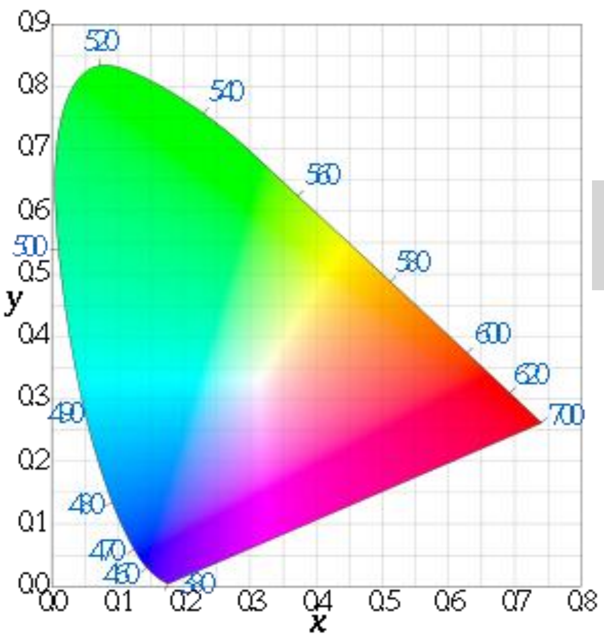
- Spectral distribution of light emitting devices or light sources
  - To realize colors to be recognized by human eyes



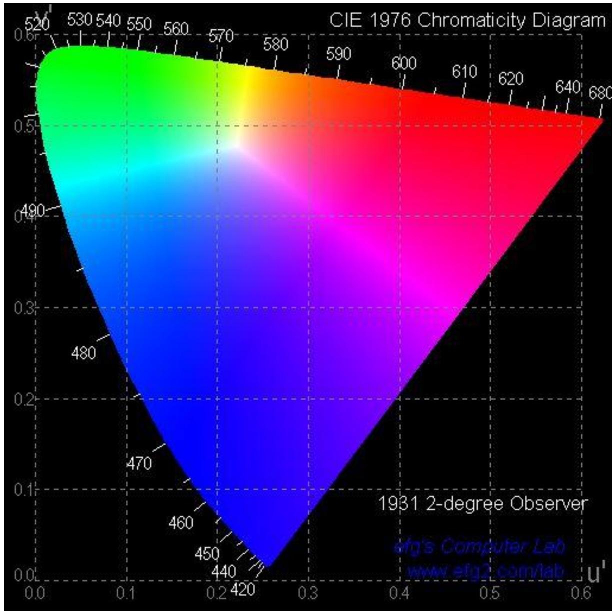

RGB LED spectral response
An example

# FACTORS CONSIDERED FOR OWC MODULATION (3)

- Light color spaces
  - Light color spaces can be defined.
    - A point in a color space represents a color of light.
    - Linearity and uniformity work in the space for mixing multiple light signals to generate a light signal having a specific color.



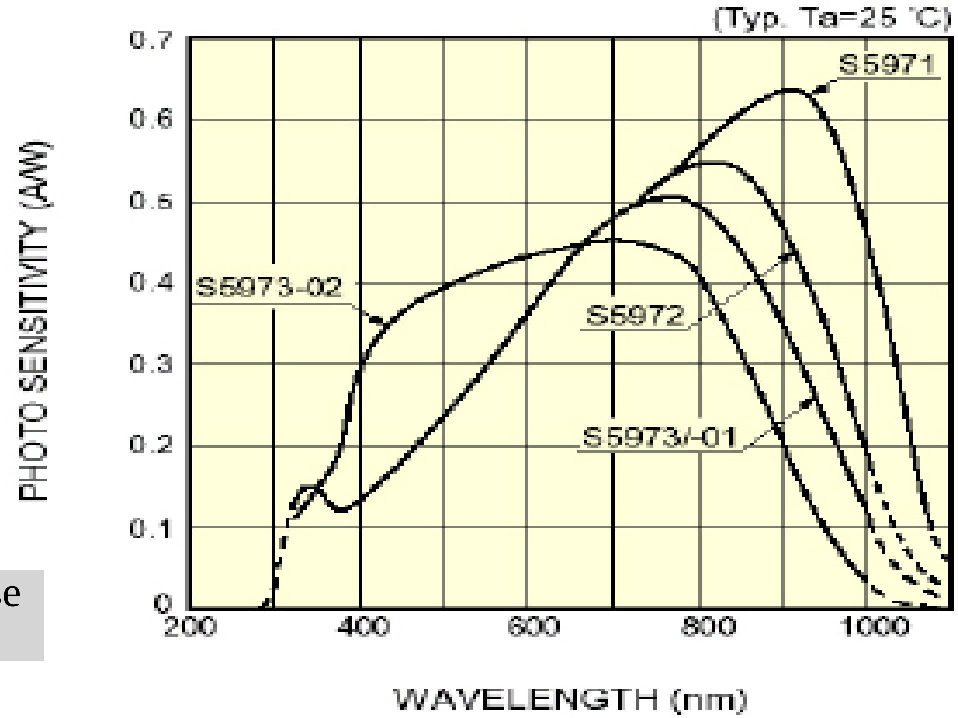

**<u>1931 CIE *xy* Color space</u>**




**<u>1976 CIE *u'v'* Color space</u>**

# FACTORS CONSIDERED FOR OWC MODULATION (4)

- **Responsivities** of photo detection devices
  - Photo detection devices have different responsivities for each wavelength.
  - At the receiver, post emphasis may be needed to compensate perceptual non-uniformity.



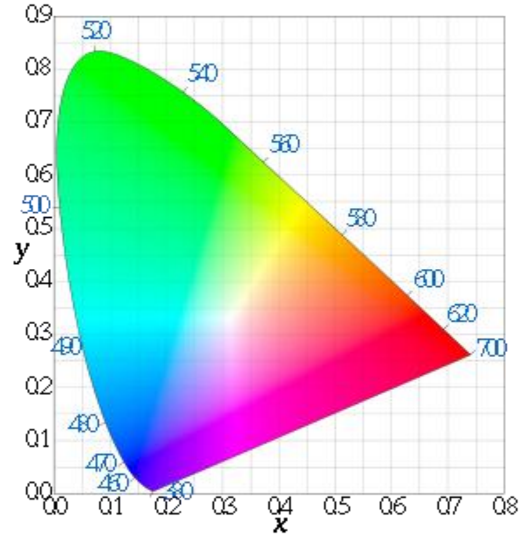

Silicon PD spectral response
An example

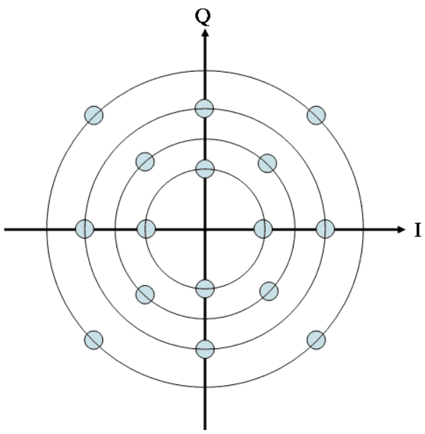
# FACTORS CONSIDERED FOR OWC MODULATION (5)

- Colors or comfortableness of light output from light emitting devices after modulation
  - After modulation, any of target colors should be able to be generated: **to human eyes.**
  - To mix multiple colors to generate any target color, a set of color coordination coefficients (or intensities of light sources) should be considered.
- Communications should not degrade illumination efficiency.
  - Compatible with dimming: no or minimum performance degradation due to dimming
- Efficiency of constellation map in a light color space after considering all factors
  - The above factors should be considered to design a constellation map, given a target color and the number of constellation points.

# BASIC CONCEPT: MULTI COORDINATES TO REPRESENT COLORS (1)

- In the modulation scheme suggested in this document, two coordinates (*x* and *y*) for a two dimensional light color space are considered.
  - *x* and *y* are designed to be orthogonal to each other to be applied for the scheme:
    - No correlation between these two.
    - Any point in a space can be represented by a unique pair of these values.
    - A color is represented by a unique point in a space, not by multiple points.
  - Similar to QAM
    - Determine points which maximize the minimum distance among distances between any two points.
    - Equi-distance strategy is a possible way to assign points.



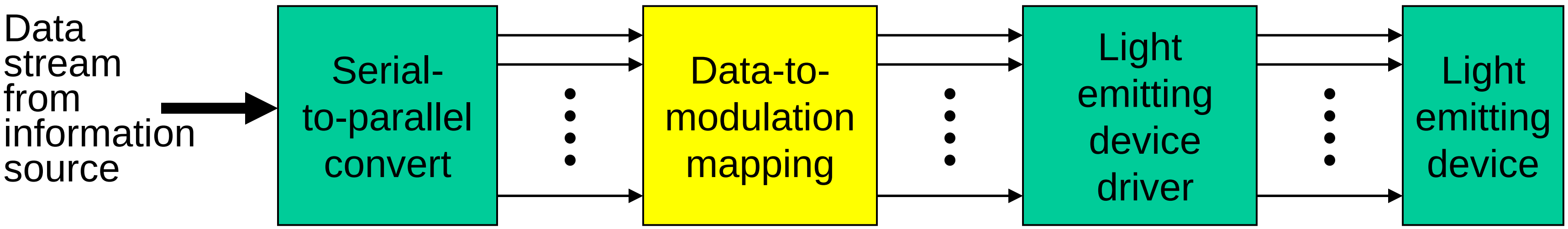



# BASIC CONCEPT: MULTI COORDINATES TO REPRESENT COLORS (2)

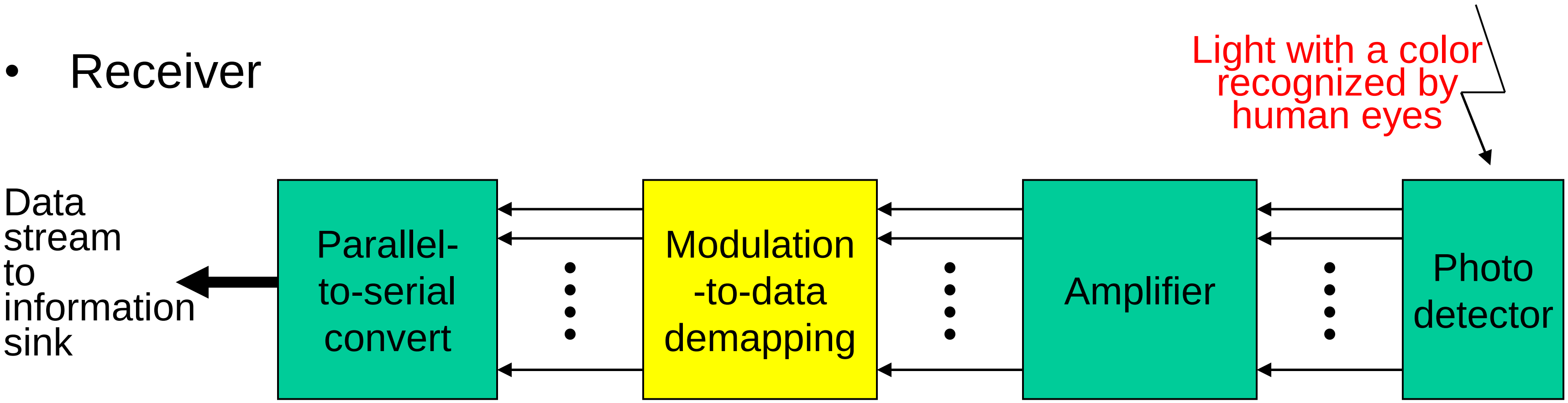
- A color can be generated by mixing lights from multiple light emitting devices such as LEDs: multiple light sources based, not single light source based
  - It is not necessary that light of a color can be generated by mixing light signals from multiple light emitting devices with a unique set of light intensities of light emitting devices.
  - A multi dimensional space can be considered to represent colors.
  - → A multi dimensional light color space can be used for color representation, but generally it is not true that there is only one point to represent each color: multiple points can be identified for a specific color.
  - → Thus a light space should be well tailored not to have multiple points to represent a color, but to represent a color with a unique point.

# MODULATION BLOCKS

- Transmitter




- Receiver



# CIE 1931 COLOR SPACE (1)

The CIE *xy* chromaticity diagram and the CIE *xyY* color space

- The outer curved boundary is the spectral (or monochromatic) locus, with wavelengths shown in nanometers.
- The concept of color can be divided into two parts: brightness and chromaticity.
- The *Y* parameter is a measure of the brightness or luminance of a color.

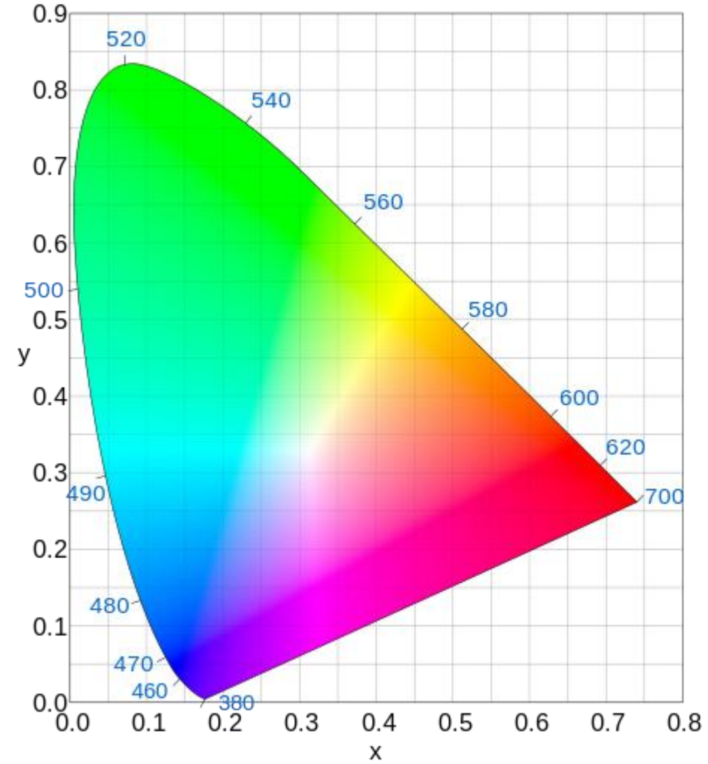
$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z} = 1 - x - y$$

$$X = \frac{Y}{y}x$$

$$Z = \frac{Y}{y}(1 - x - y)$$



# *CIE 1931 COLOR SPACE (2)*

One important fact on CIE *xyY* color space

- The CIE 1960, CIE 1964, and CIE 1976 color spaces were developed, with the goal of achieving **perceptual uniformity** (to have an equal distance in the color space correspond to equal differences in color).
- Although they were a distinct improvement over the CIE 1931 system, they were not completely free of distortion.

→ To utilize better perceptual uniformity, the CIE 1976 is more appropriate for a color space for modulation schemes using the constellation planes in a light color space including one suggested in this document. And also it has less area that can not be covered by a triangle made with any three point colors.

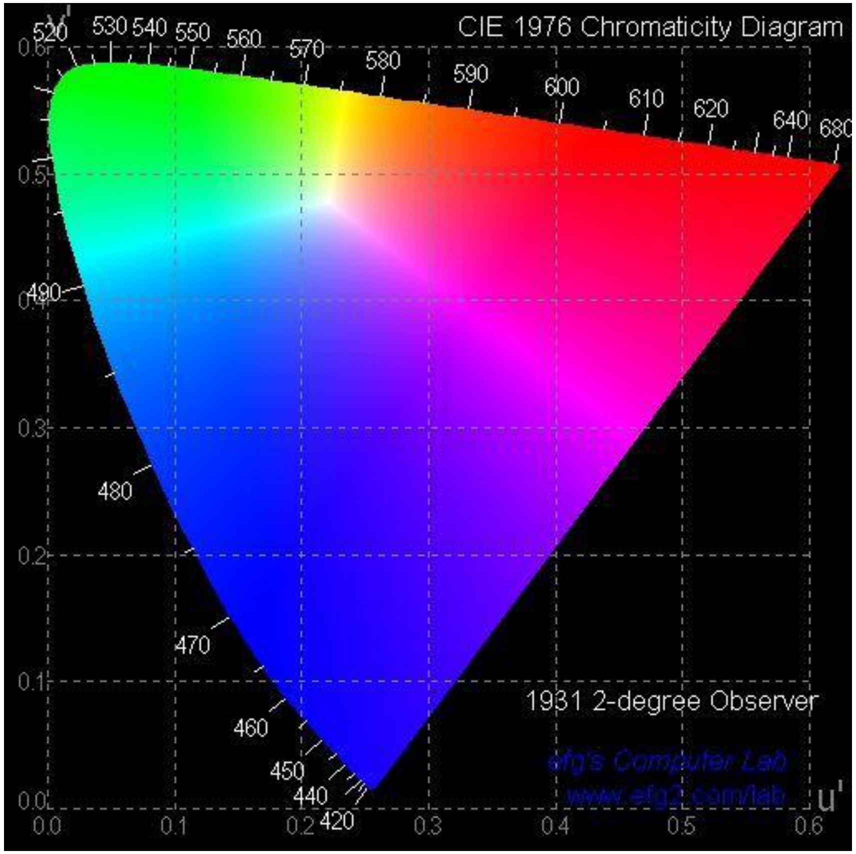
# 1976 CIE u'v' COLOR SPACE

1976 CIE *u'v'* (or CIE *LUV*) Chromaticity Diagram (1)

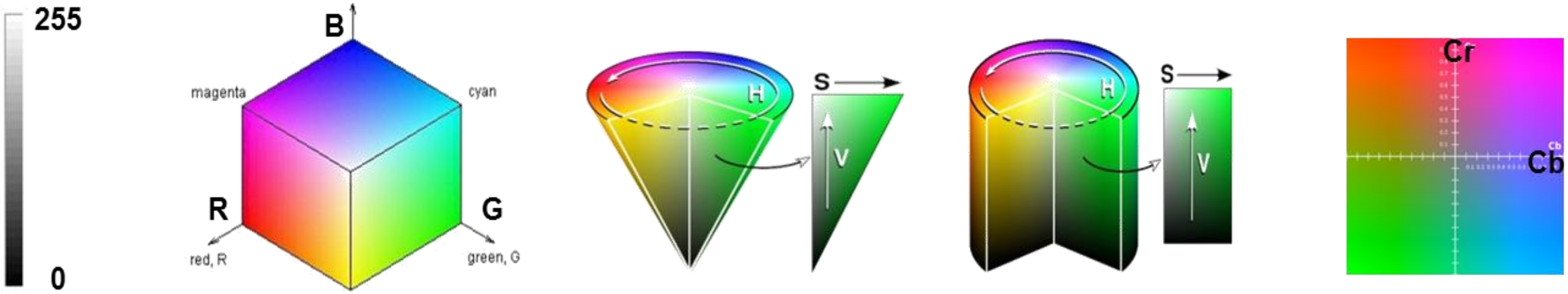
- The advantage of the 1976 diagram is that the distance between points is now approximately proportional to the perceived color difference, which is definitely not true in the 1931 diagram.

  →attempted perceptual uniformity

  →additive mixtures of different colored lights will fall on a line in CIE *LUV's* uniform chromaticity diagram with a condition that the mixtures are constant in lightness.



# VARIOUS CONSTELLATION DIAGRAM TYPES




Gray RGB HSV(conic) HSV(cylindric) YCbCr(YUV)

# *BASIC CONCEPT (1)*

- Transmission and reception (or detection) of light signals
  - At the transmitter, multiple light sources (or light emitting devices) such as LEDs with different spectral distributions are used for light emission.
  - At the receiver, multiple photo detectors with different spectral responses are used for light signal detection.
- Any color can be represented by a point in a multi-dimensional space uniquely.
  - Any color is represented by a point in an *n* dimensional space. It is because in general light generated by each device can also be generated by mixing light signals from other devices which have different spectral distributions.

  → Thus multi-dimensional space should be defined to represent a color with a point uniquely in this space.
  - **A unique color for a point in a space can be generated by mixing light signals emitted from *n* light emitting devices and be detected by processing light signals detected by *k* photo detectors.**

# *BASIC CONCEPT (2)*

Light Signal Delivery Model from Transmitter to Receiver

- Radiation at Transmitter
  - Multiple light emitting devices emit light signals at transmitter. Each device has its own **spectral distribution, *S(λ),*** which determines its emitted power by calculating total power throughout the whole wavelength range.
  - By using the color matching functions of a light space and by calculating stimulus values –for two dimensional space, *X*, *Y* and *Z* values -of the light space, the color of emitted light perceivable by human eyes can be determined.
  - By using these values, a point of a light signal in a color space can be determined.

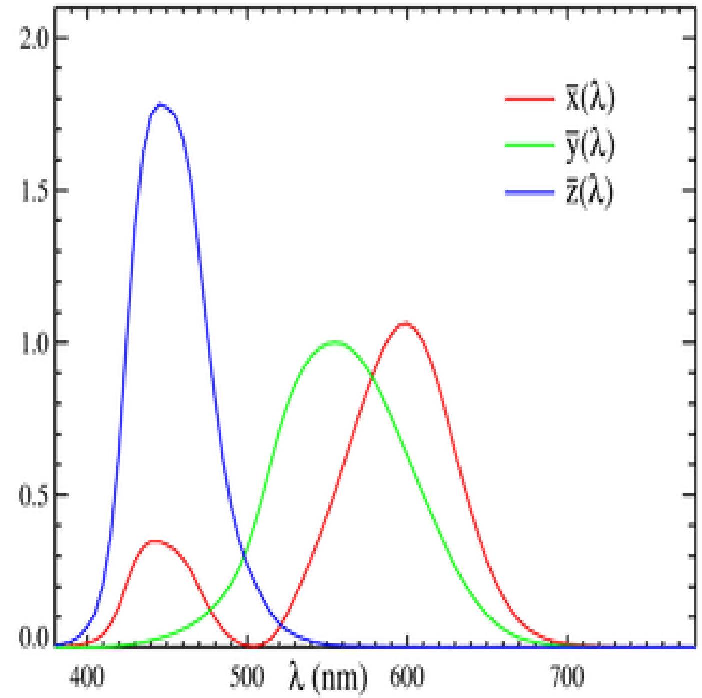
# BASIC CONCEPT (3)

Light Signal Delivery Model from Transmitter to Receiver

- Radiation at Transmitter: An example with CIE 1931 color space
  - Color matching functions
    - a set of three *color-matching functions*, called $\overline{x}(\lambda)$ , $\overline{y}(\lambda)$ and $\overline{z}(\lambda)$
  - For spectral power distribution, $I(\lambda)$, three stimulus values

$$X = \int_0^\infty I(\lambda)\,\overline{x}(\lambda)\,d\lambda$$
$$Y = \int_0^\infty I(\lambda)\,\overline{y}(\lambda)\,d\lambda$$
$$Z = \int_0^\infty I(\lambda)\,\overline{z}(\lambda)\,d\lambda$$

where $\lambda$ is the wavelength of the equivalent monochromatic light (measured in nanometers).



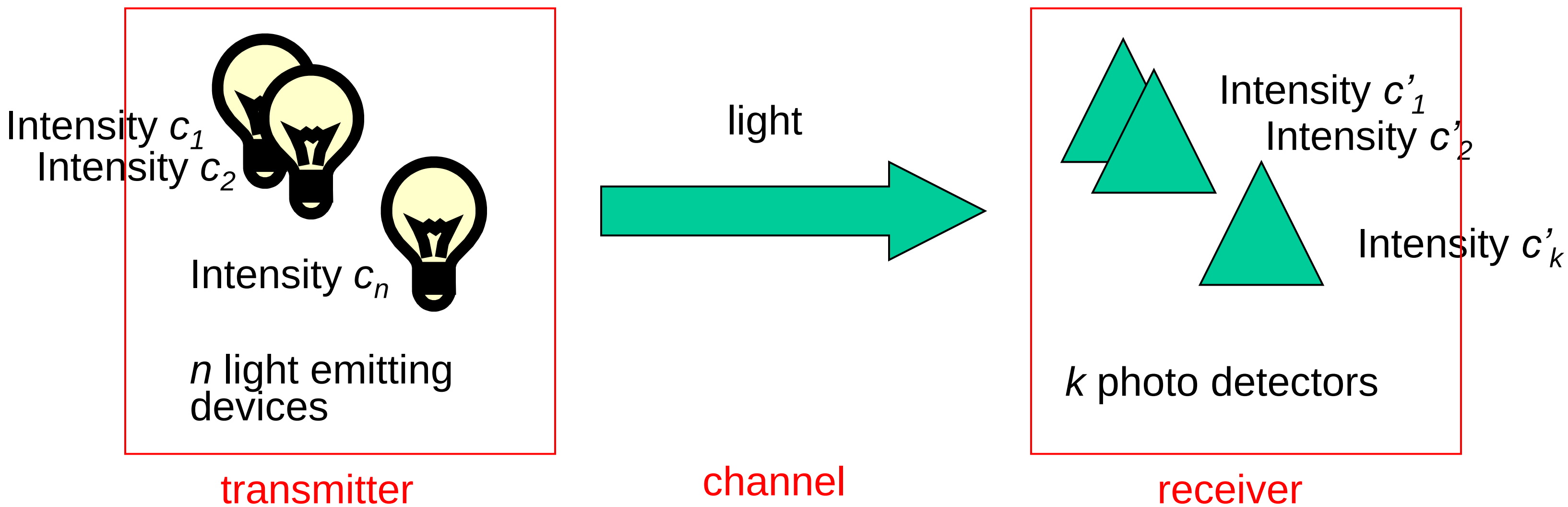
# *BASIC CONCEPT (4)*

<u>Light Signal Delivery Model from Transmitter to Receiver</u>

- Perception by Human Eyes
  - To know how human eyes react to emitted light:
    - An emitted light signal which has a spectral distribution, *S(λ),* is multiplied by a standardized luminosity function - wavelength-weighted by the luminosity function to correlate with human brightness perception. Then total power perceived by human eyes can be determined.
- Detection at Receiver
  - The emitted signal is delivered to the detector which is characterized by its responsivity, its own spectral sensitivity, which determines the spectral characteristics of the received light signal and total received power to determine a color detected.

# BASIC CONCEPT (5)

Light Signal Delivery Model from Transmitter to Receiver Intensity



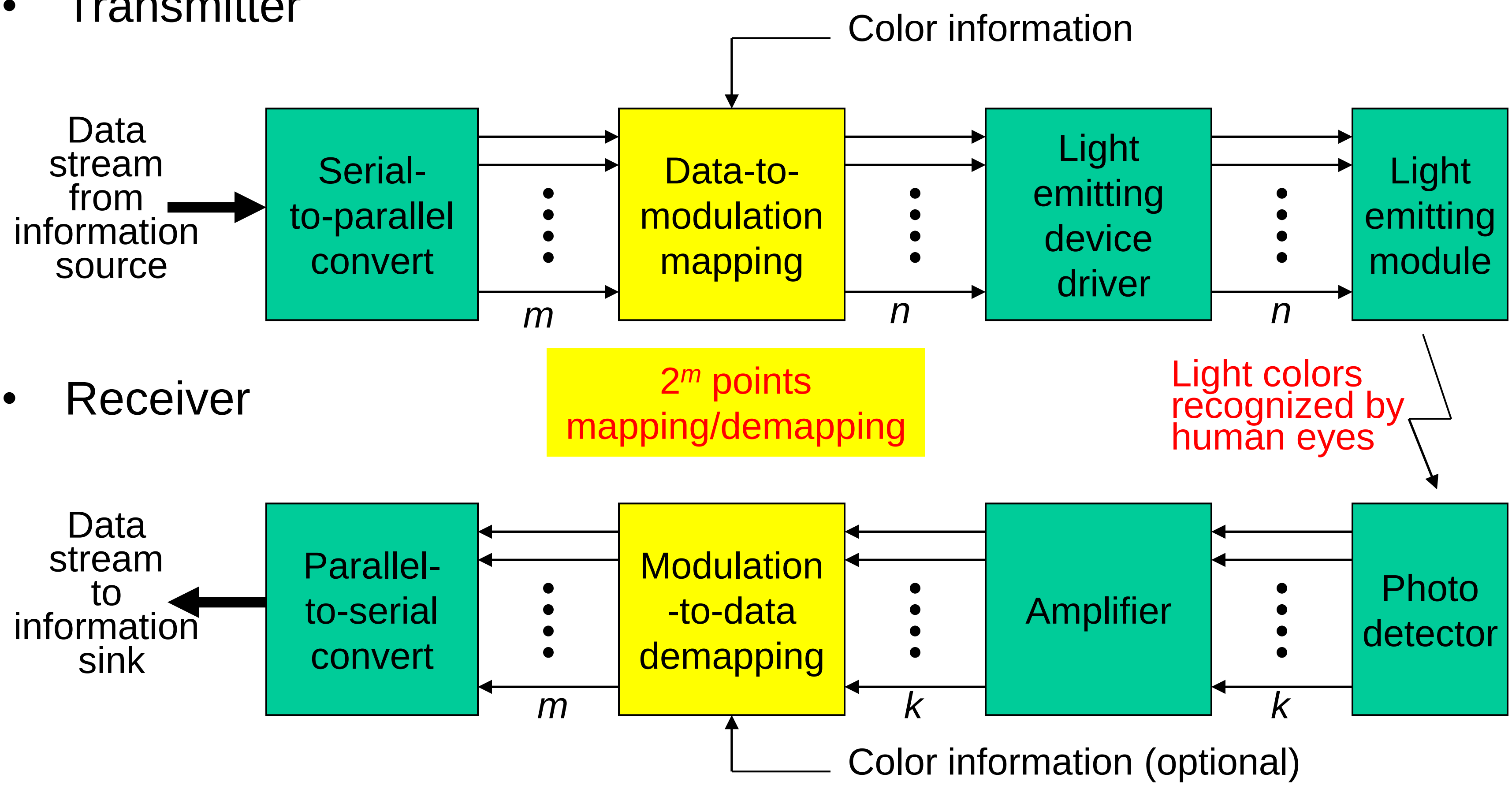

$c_{total} = c_1 + c_2 + \ldots + c_n$
*where* $c_i = \int s_i(\lambda) d\lambda$

$c'_{total} = c'_1 + c'_2 + \ldots + c'_k$
*where* $c'_i = \int s'_i(\lambda) d\lambda$

Transmitted light power: $\sum \int s_i(\lambda) d\lambda$ + noise interference = Received light power: $\sum \int s'_i(\lambda) d\lambda$

# MODULATION BLOCKS REVISITED

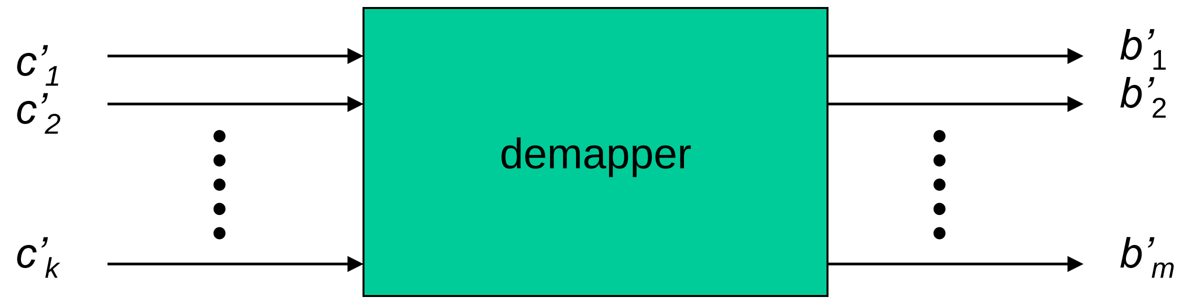
- Transmitter
- Receiver



# MODULATION MAPPING

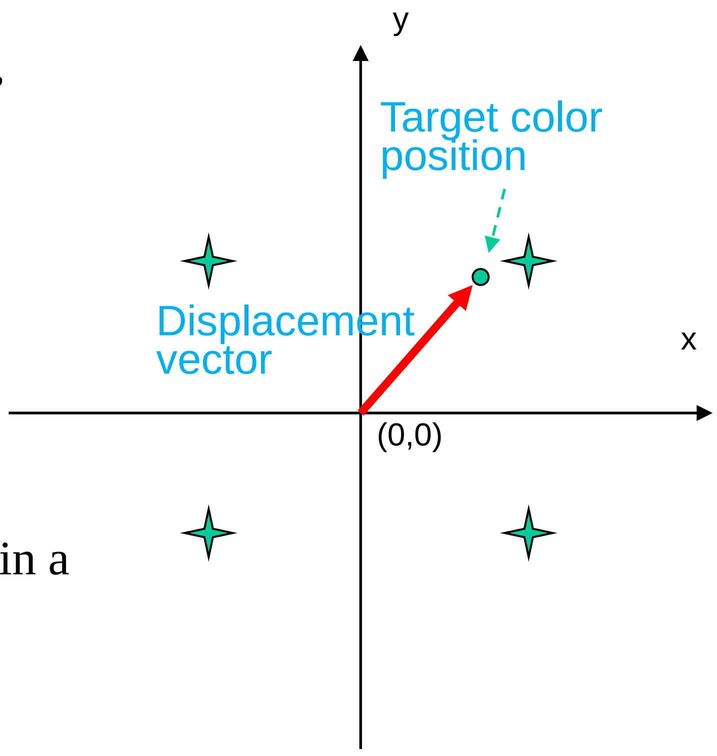
Data-to-modulation mapping (transmitter)


Modulation-to-data demapping (receiver)



# GENERATION OF CONSTELLATION (1)

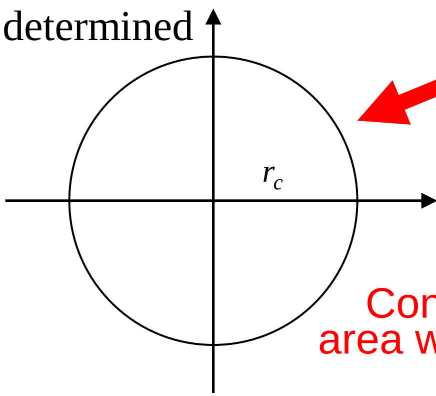
- Assumptions
  - Equi-probable data elements
  - For duration of a fixed number of symbols, color is not changed.
- Input
  - Information data: $m$ bits → $2^m$ symbol elements → $2^m$ points
  - Color information: $(x_c, y_c)$
- Output
  - Constellation: $(\boldsymbol{x}, \boldsymbol{y})$
- Two parameters considered to pick points in a light space
  - Colors perceptible by human eyes
  - Equi-distance between two adjacent points when points are detected by photo detectors



# GENERATION OF CONSTELLATION (2)

- Maximum area of constellation is determined by two factors:
  - Point of a target color visible to human eyes: this point becomes the origin of constellation.
  - Gamut formed by primary color points which represent points of light emitting devices used.

  → Maximum constellation area determined

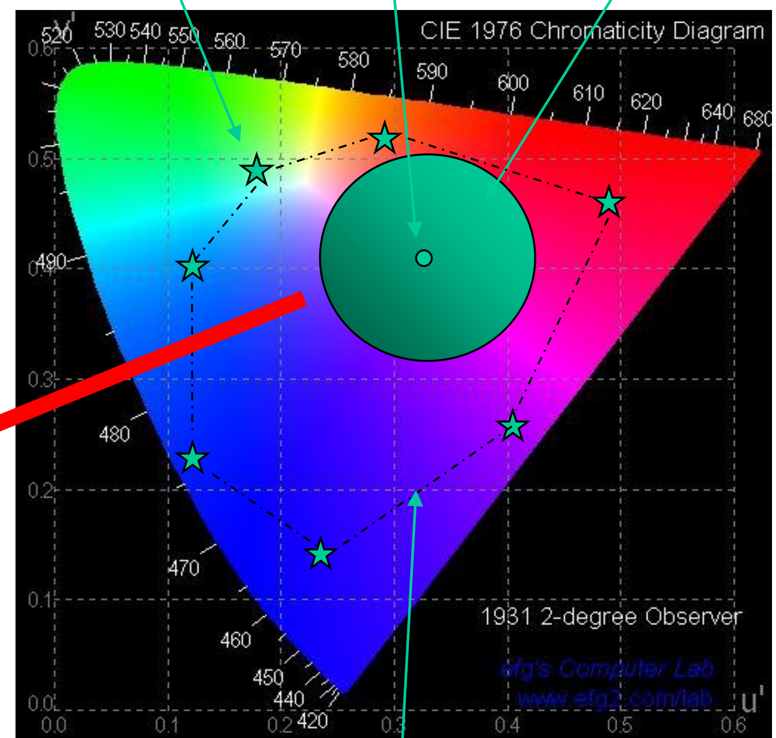



Constellation area with radius $r_c$

Point of target color

Point of a light emitting device

Max area of constellation



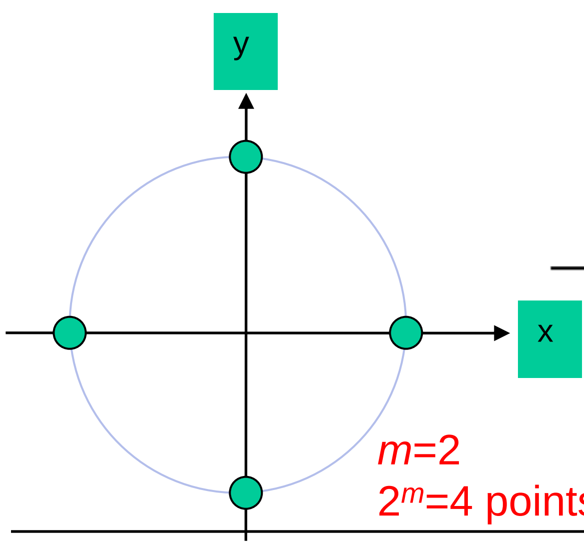

Gamut formed by seven light emitting devices

# GENERATION OF CONSTELLATION (3)

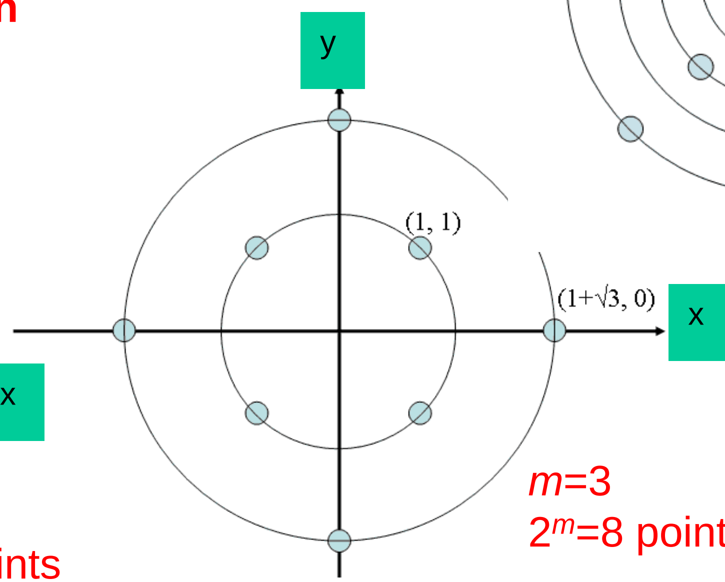
<u>Normalized constellation</u>

Inside a unit circle centered at the original, $2^m$ points are assigned so that the minimum distance between any two points be maximized.

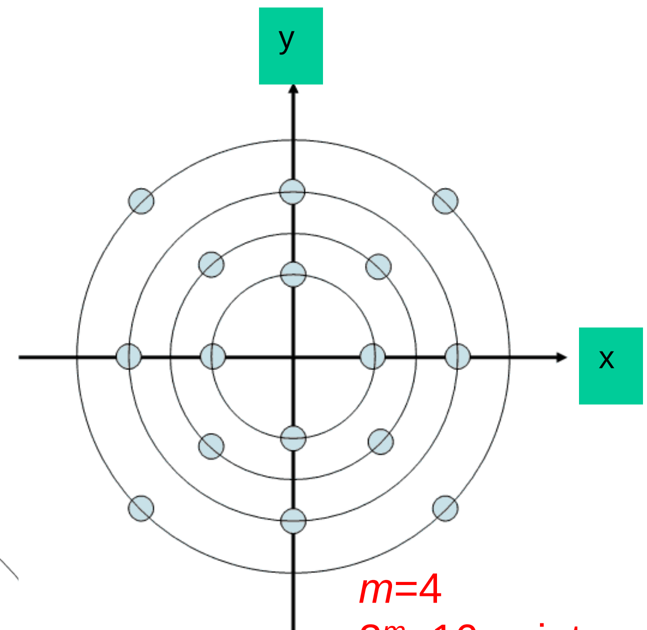
**Examples of constellation**




$m$=2
$2^m$=4 points




$m$=3
$2^m$=8 points

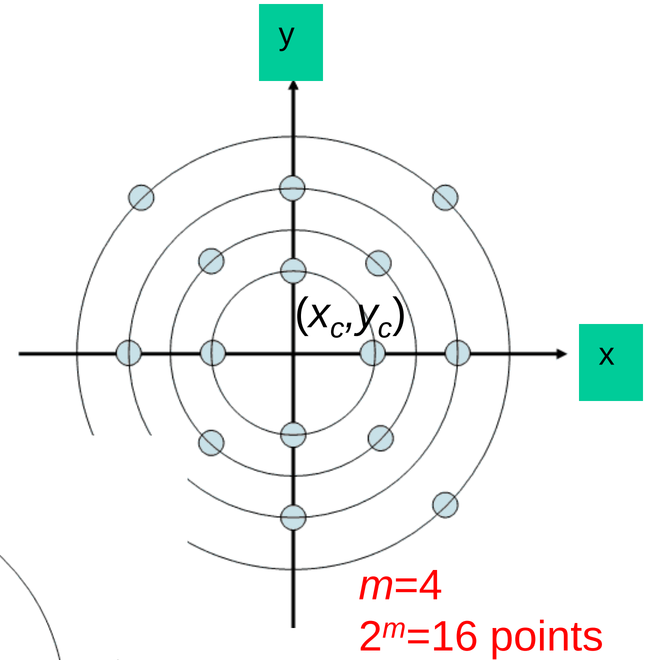


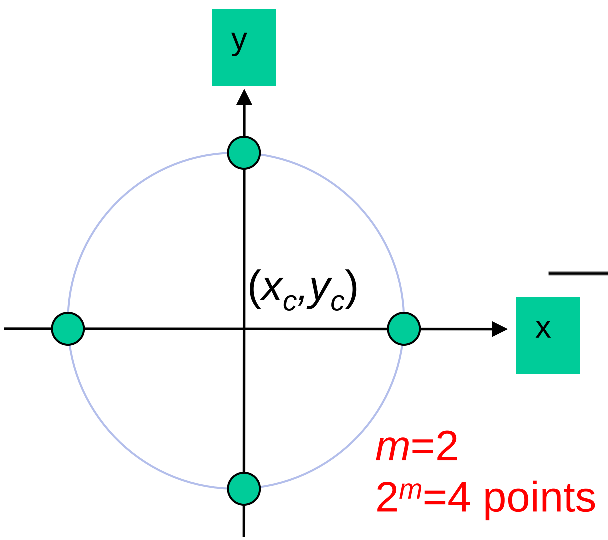

$m$=4
$2^m$=16 points

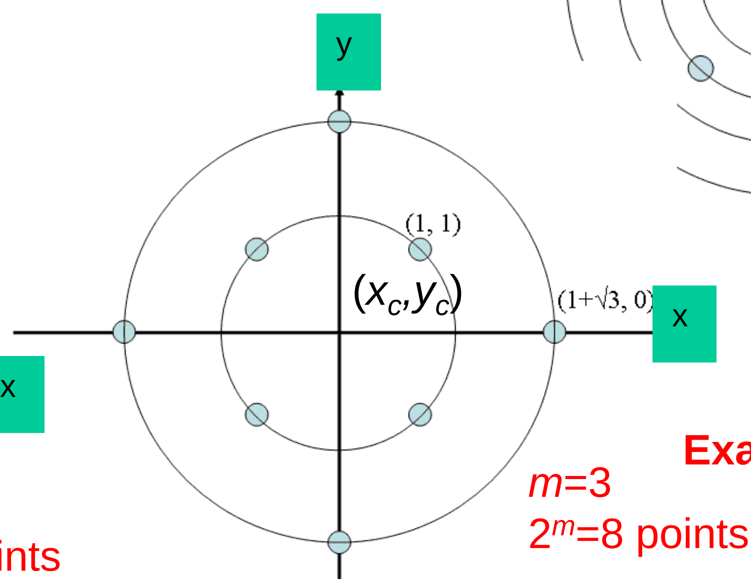
# GENERATION OF CONSTELLATION (4)

Constellation moved to the center of target color location

Normalized constellation generated is shifted so that the center is located at the target color point and the constellation is scaled so that constellation area fits the maximum area with a radius of $r_c$.




**Examples of constellation**

# CONSTELLATION TO ($c_1$, $c_2$, . . ., $c_n$) MAPPING

- Assumption
  - Perceptual uniformity or linearity of light emitting devices and photo detectors in the light space
- Input/output
  - Input: Constellation: ($\boldsymbol{x},\boldsymbol{y}$)
  - Output: ($c_1$, $c_2$, . . . , $c_n$)
- Two cases for color properties of light emitting devices
  1. Using ($x_i$,$y_i$) $i$=1, 2, .., $n$ for all light emitting devices if ($x_i$,$y_i$) $i$=1, 2, .., $n$, is given
  2. Using spectral distributions of light emitting devices if ($x_i$,$y_i$) $i$=1, 2, .., $n$, is not given

# ($c'_1$, $c'_2$, . . ., $c'_k$) TO CONSTELLATION DEMAPPING

- Assumption
  - Uniformity or linearity of light emitting devices and photo detectors in the light space
  - The receiver has constellation information that the transmitter applies.
- Input/output
  - Input: ($c'_1$, $c'_2$, . . . , $c'_k$): light intensities measured by photo detectors: noise added from channels to produce these coefficients
  - Output: information point, (***x'***, ***y'***), in a constellation most closely matching to a set of light intensities, ($c'_1$, $c'_2$, . . . , $c'_k$)
- Two cases for color detection properties of photo detectors

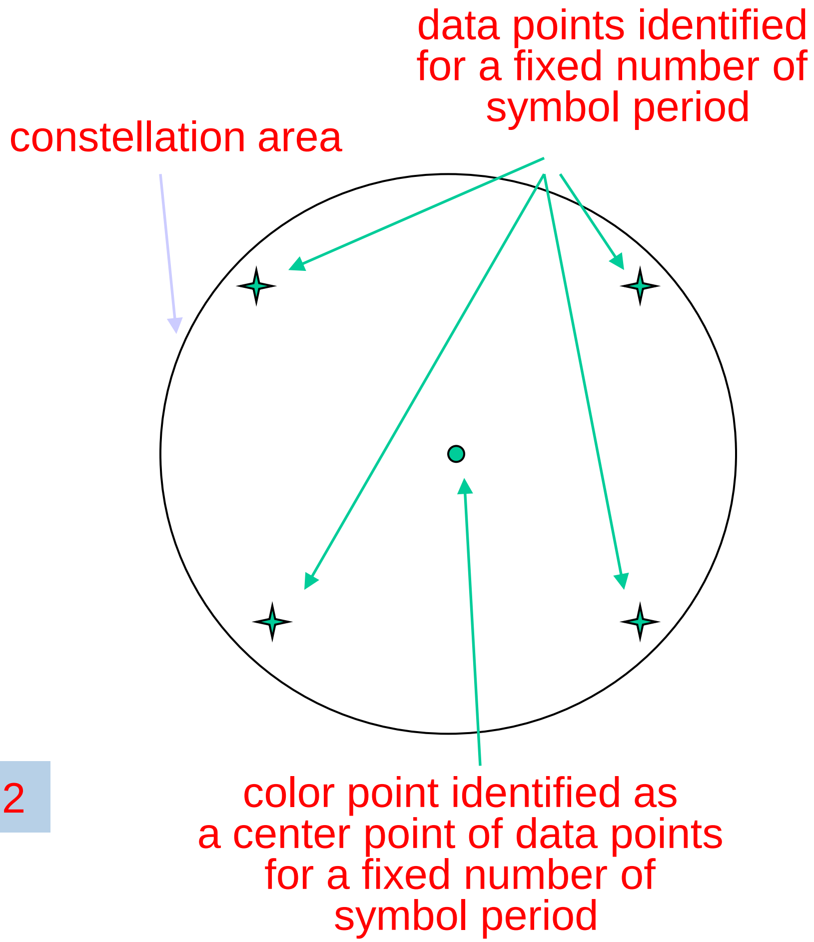
  1. Using ($x'_i$,$y'_i$), $i=1, 2, .., k$, for all photo detectors if these values are given
  2. Using spectral distributions of photo detectors if ($x'_i$,$y'_i$), $i=1, 2, .., k$, is not given

# COLOR INFORMATION FROM CONSTELLATION

How to extract color information at receiver?

Two cases

1. Transmitter sends color information ($x_c$,$y_c$): TV signals, etc.
2. Using a fixed number of received symbols, color information can be extracted.




For an example for $m$=2

# INFORMATION DATA FROM CONSTELLATION (1)

With an assumption that

- Gamut formed by photo detectors should include all area of gamut formed by light emitting devices at transmitter. If not, some distortion is inevitable.

How to extract constellation scaling factor for a color at receiver?

How to get a constellation at receiver?

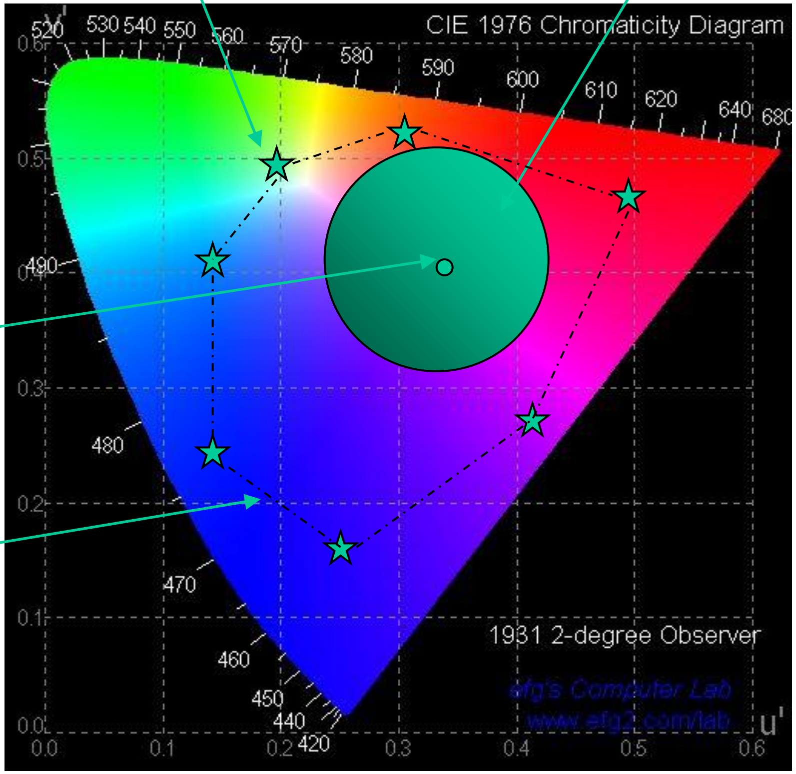
Some cases can be considered:

1. Periodically the transmitter broadcasts information on light emitting devices used.
2. Whenever color changes or periodically with a fixed interval, transmitter broadcasts scaling factor information with color information.
3. **Without any information listed above, the receiver can know color information and constellation by examining points of a fixed number of previously received symbols.**

# INFORMATION DATA FROM CONSTELLATION (2)

<u>Case that target color information delivered from transmitter (Case 1)</u>

Extraction of information data from received signals



# INFORMATION DATA FROM CONSTELLATION (3)

Calculation of ($x'$, $y'$)

- Basic equations to calculate ($x'$, $y'$), position of a received light in the light space

$$x' = \frac{\sum_i c_i' x_i'}{\sum_i c_i'}$$

$$y' = \frac{\sum_i c_i' y_i'}{\sum_i c_i'}$$

For the case that ($x_i'$,$y_i'$) $i$=1, 2, .., $k$ is given

For the case that spectral distributions of all light emitting devices are given,

since $c_i = X_i + Y_i + Z_i$,

$$x' = \frac{\sum_i \frac{c_i' \int s_i'(\lambda)\bar{x}(\lambda)d\lambda}{X_i' + Y_i' + Z_i'}}{\sum_i c_i'} = \frac{\sum_i \int s_i'(\lambda)\bar{x}(\lambda)d\lambda}{\sum_i c_i'}$$

$$y' = \frac{\sum_i \frac{c_i' \int s_i'(\lambda)\bar{y}(\lambda)d\lambda}{X_i' + Y_i' + Z_i'}}{\sum_i c_i'} = \frac{\sum_i \int s_i'(\lambda)\bar{y}(\lambda)d\lambda}{\sum_i c_i'}$$

($c_1'$ $c_2'$, .., $c_k'$) is given.→ need to calculate $x'$ and $y'$.

# WHY THIS MODULATION ? MOTIVATION TO CSM (1)

- Not affected by light intensity and intensity variation: not intensity modulation
  - Only related to positions of signals in a light space
  - Dimming control is not a problem to implement.
- Any colors can be generated, visible to human eyes: independent of colors
  - Independent of color of light signal from each light source
  - Any target color can be generated perceivable to human eyes
- Progressive modulation can be achieved without any serious burden
  - Low to high data rates can be achieved with a common constellation (scheme) corresponding to various applications
  - By varying number of points in a constellation and symbol periods
    - An example
      - Lower data rate for remote controlling: 2-CSM, 1 symbol/4 symbol periods→ 1/4 bit/symbol period
      - Higher data rate for file transfer: 64-CSM, 1 symbol/1 period → 6 bits/symbol period

→ Adaptive to various data rates and colors

# WHY THIS MODULATION ? MOTIVATION TO CSM (2)

- Colors of light sources: adaptive to various colors

| Application category | colors |
|---|---|
| Traffic light –vehicle | red, green and amber |
| Vehicle–vehicle | can be determined in favor of modulation scheme applied |
| Infra-vehicle (outdoor) | can be determined in favor of modulation scheme applied |
| Infra-mobile (indoor low speed) or Infra-fixed (indoor fixed) | can be determined in favor of modulation scheme applied |
| Infra-mobile (indoor high speed) | white/illumination |
| Mobile/fixed-mobile | can be determined in favor of modulation scheme applied |

# WHY THIS MODULATION ? MOTIVATION TO CSM (3)

- With peak available transmit power fixed,
  - Use full power for data representation: more power can be used for transmission for the case of confined peak power.
  - → Higher average transmit power
  - → Longer range
  - → Lower BER
  - → **more desirable**.
- **Self identification of colors of light signals detected**
  - should not depend on the color transmitted
  - should not depend on the intensity of transmitted signals
    - Not intensity modulation, but constellation modulation in a color space: each point (or symbol) represented by two coordinates in a color space

# WHY THIS MODULATION ? MOTIVATION TO CSM (4)

- Simple implementation
  - At the transmitter
    - Given *x* and *y* coordinates or spectral distributions of ***n*** **light emitting devices** in a light space used for the light sources by manufacturers
    - **Only a look-up table** applied for data to intensities mapping for $2^m$ CSM
  - At the receiver
    - Given *x* and *y* coordinates or spectral responses of ***k*** **photo detection devices** in a light space used for the light signal detection by manufacturers
    - **A simple formula** applied for intensities to data demapping for $2^m$ CSM

# SIMULATION RESULTS USING CIRS GIVEN (1)

- Scenario 1 → a) Open Office → D1~24

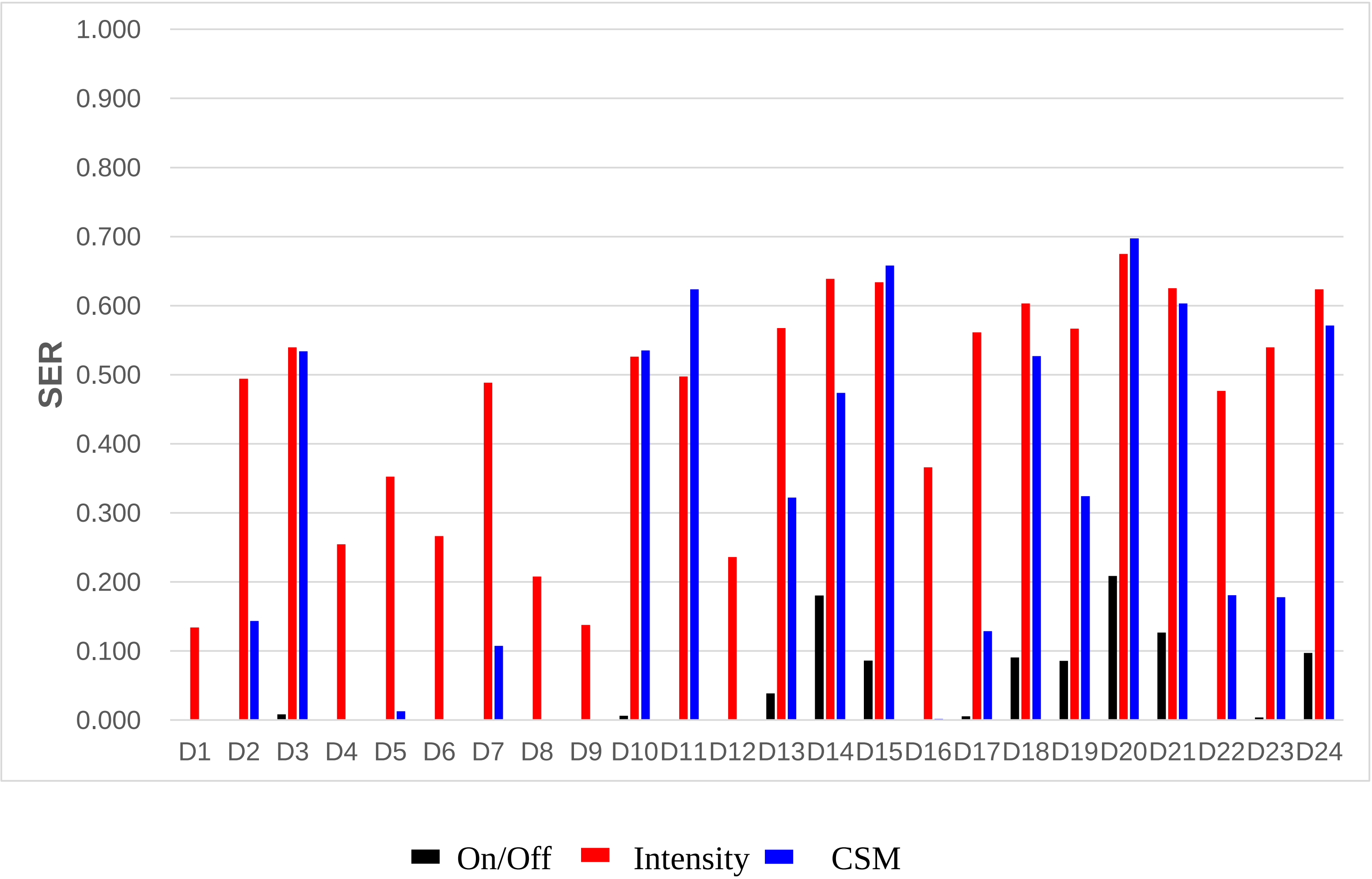
Table 1. Simulation parameters for open office/office with cubicles

| | |
|---|---|
| **Room size** | 14m × 14m × 3m |
| **Materials** | Walls: Plaster, Ceiling: Plaster, Floor: Pinewood |
| **Objects** | 6 desks and a chair, 6 laptops on each desk,<br>6 cubicles (optional) 9 human bodies |
| **Objects specifications** | Cubicles: Plaster<br>Desk: Pinewood (Typical height of 0.85m)<br>Chair: Pinewood<br>Laptop: Black gloss paint<br>Human body:<br>▪ Shoes: Black gloss paint<br>▪ Head & Hands: Absorbing<br>▪ Clothes: Cotton |
| **Luminary Specifications** | Brand: LR24-38SKA35 Cree Inc.<br>Half viewing angle: 40° |
| **Number of luminaries** | 32 |
| **Receiver Field of View** | 85 degrees |
| **Receiver area** | 1 $cm^2$ |

# SIMULATION RESULTS USING CIRS GIVEN (2)

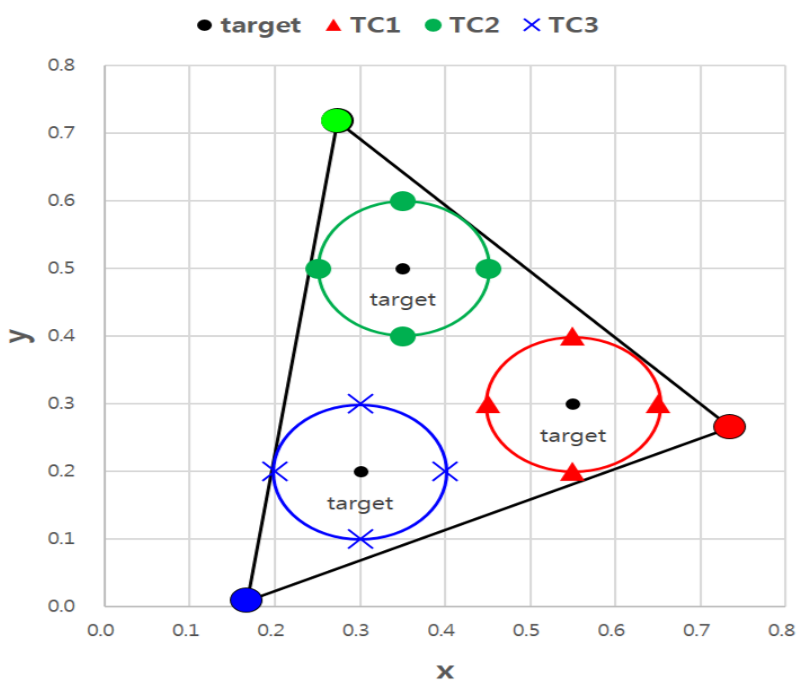
| location | color | SER (Symbol Error Rate) - 10000 symbols test | | |
|---|---|---|---|---|
| | | On/Off | Intensity (4 levels) | CSM (4 symbols) |
| D1 | blue | 0.000 | 0.134 | 0.000 |
| D2 | blue | 0.000 | 0.494 | 0.144 |
| D3 | blue | 0.008 | 0.540 | 0.534 |
| D4 | blue | 0.000 | 0.254 | 0.000 |
| D5 | blue | 0.000 | 0.352 | 0.013 |
| D6 | blue | 0.000 | 0.267 | 0.000 |
| D7 | blue | 0.000 | 0.489 | 0.107 |
| D8 | blue | 0.000 | 0.208 | 0.000 |
| D9 | blue | 0.000 | 0.138 | 0.000 |
| D10 | blue | 0.006 | 0.526 | 0.535 |
| D11 | blue | 0.000 | 0.498 | 0.624 |
| D12 | blue | 0.000 | 0.236 | 0.000 |
| D13 | red | 0.038 | 0.567 | 0.322 |
| D14 | red | 0.181 | 0.639 | 0.474 |
| D15 | red | 0.086 | 0.634 | 0.658 |
| D16 | red | 0.000 | 0.366 | 0.002 |
| D17 | red | 0.005 | 0.561 | 0.129 |
| D18 | red | 0.090 | 0.603 | 0.527 |
| D19 | green | 0.086 | 0.567 | 0.324 |
| D20 | green | 0.209 | 0.675 | 0.697 |
| D21 | green | 0.127 | 0.625 | 0.603 |
| D22 | green | 0.000 | 0.477 | 0.181 |
| D23 | green | 0.004 | 0.540 | 0.178 |
| D24 | green | 0.097 | 0.624 | 0.571 |

# SIMULATION RESULTS USING CIRS GIVEN (3)

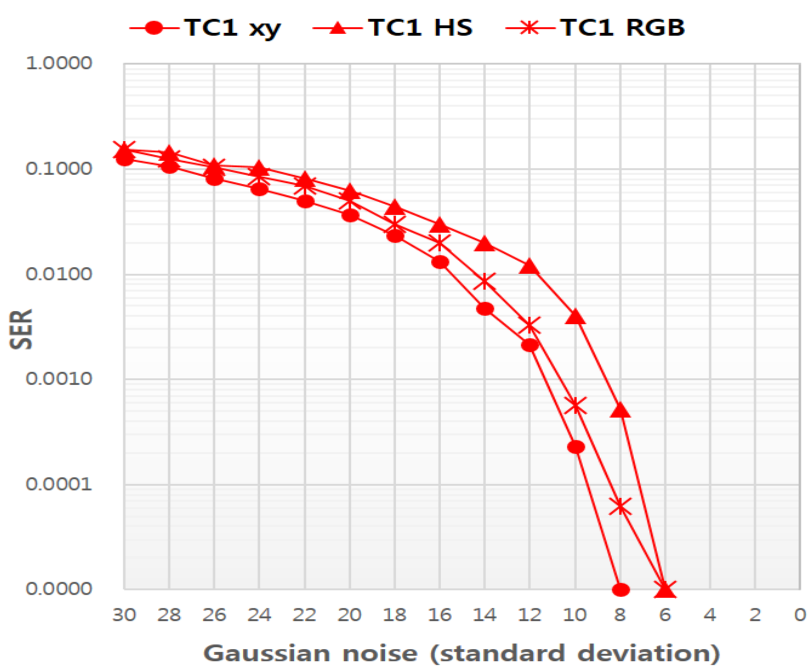


# SER COMPARISON ON COLOR MODELS

**constellation diagram**

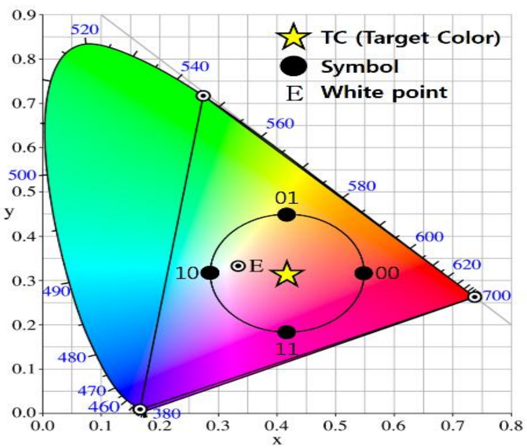


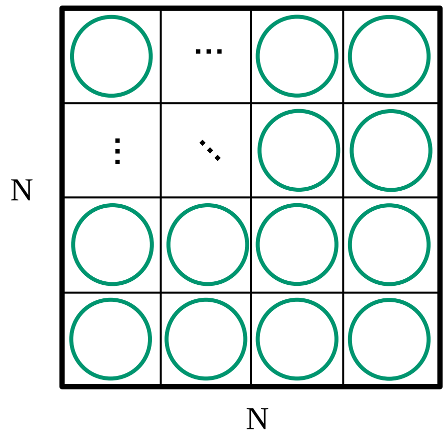

**SER graph (TC1)**

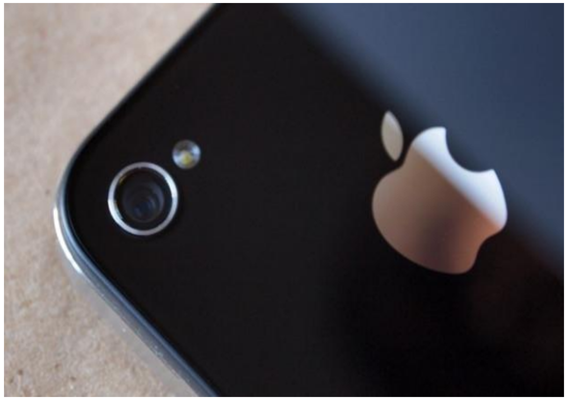



- **Symbol decision method in receiver.**
  1. x, y decision in CIE1931
  2. H, S decision in HSV model
  3. R, G, B decision in RGB model

# DATA RATES ACHIEVED



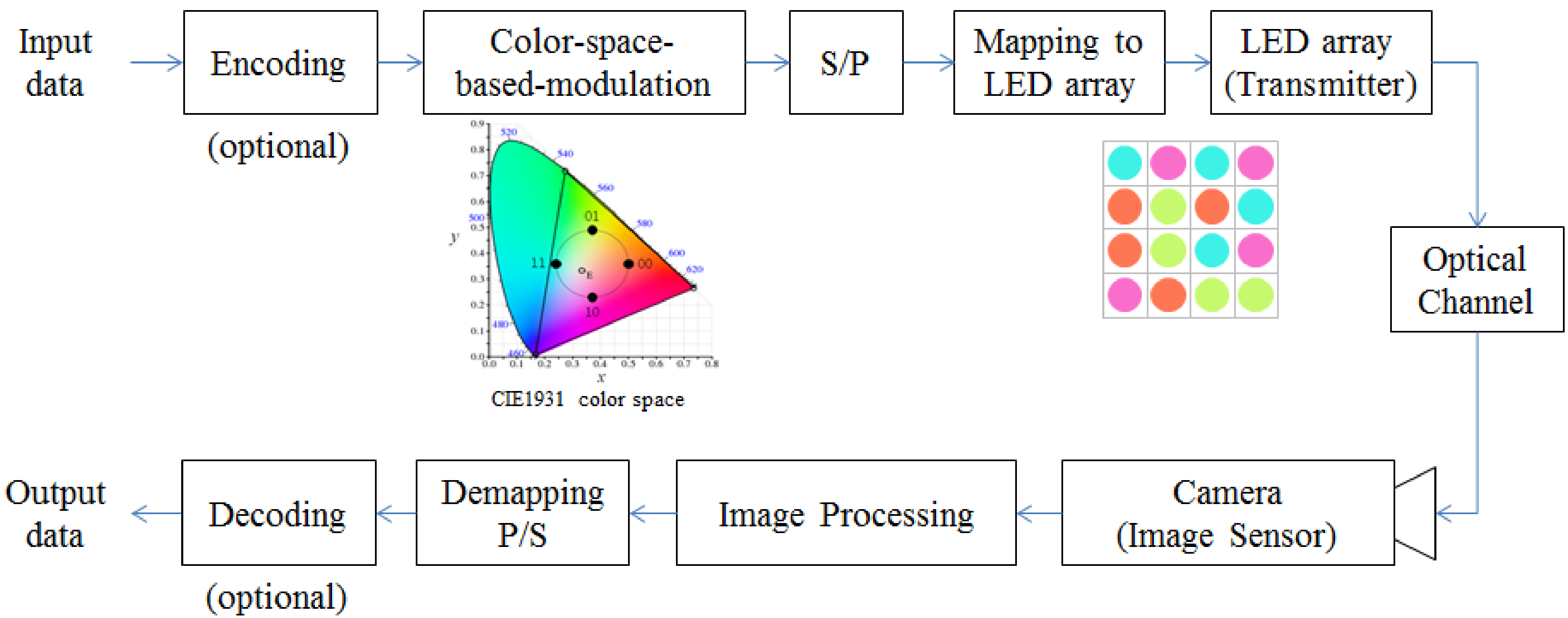



| | | |
|---|---|---|
| ▪ **Encoding**<br>Using $m(=2^n)$ symbols<br>→ n [bits/symbol] | ▪ **LED Array size**<br>$N \times N = N^2$ [symbol] | ▪ **Camera frame rate**<br>F [fps] |

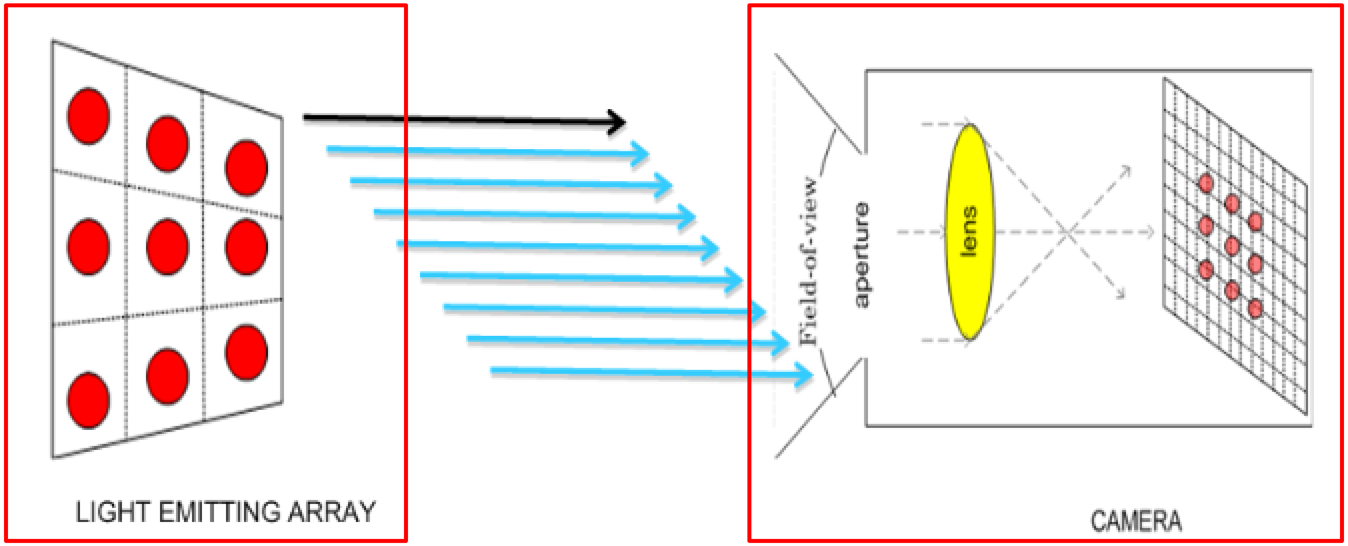
**Data rate = $n \times N^2 \times F$ [bps]**

# COLOR INDEPENDENT VISUAL-MIMO (1)




Color independent Visual-MIMO tranceiving procedure

# COLOR INDEPENDENT VISUAL-MIMO (2)




Visual-MIMO System

LEA (Light Emitting Array)
1. LED
2. Display screen

Camera or PD
1. Smart phone
2. Vehicle
3. CCTV

# CONCLUSIONS

- Color space modulation scheme proposed has many advantages
  - Independent of brightness control
    - Not to be affected by brightness control.
  - Dependency of light source (such as LEDs) characteristics
    - Modulation technique applied is not directly dependent on technical characteristics of LEDs or other light sources deployed.
  - Not (or negligibly) affected by background noise
  - Adaptiveness to various data rates
  - Simple implementation
- This modulation scheme proposed has better performance than other intensity modulations.
  - Need more simulation results .
- This modulation scheme can be applied to High Rate OWC areas while other low rate OWC areas.