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

Submission Title: Proposal for OWC Using Color Space Modulation
Date Submitted: Jan. 8, 2016

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Re: CFP of 15.7r1

Abstract: Proposal for OWC for Image sensor and high rate PD communications

Purpose: to submit a proposal for 802.15.7r1

COLOR SPACE MODULATION PROPOSED

CONSIDERATIONS FOR MODULATION

- Need of brightness control or not
  - Needs to provide superior brightness for optical wireless communications?
  - It is more desirable for performance not to be affected by brightness control.
- Dependency of LED characteristics
  - Modulation technique applied is not dependent on technical characteristics of LED or other light sources deployed.
- Not (or negligibly) affected by background noise or not
  - Offsetting the impact of background lights
  - Stable data transmission should be provided 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 speeds 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 colors to human eyes. 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 in terms of absolute power.
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 MOULATION (1)

- Eye sensitivity
  - To generate light with a color which is recognized by human eyes
  - Human eyes have different sensitivity for each wavelength: chronomicity functions reflect human eyes' sensitivity for various wavelengths.
  - To determine colors recognized by human eyes after modulation
- Spectral distribution of light emitting devices or light sources
  - To realize colors to be recognized by human eyes
- Light color spaces
  - In a constellation plane of a modulation scheme, to determine a possible area of the points where most efficient modulation can be realized, light color spaces can be defined.
  - To mix multiple colors to generate a target color, a set of color coordination coefficients in a light color space can be considered to define intensities of available color components.

FACTORS CONSIDERED FOR OWC MODULATION (2)

- 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.
- Colors or comfortableness of light output from light emitting devices after modulation
  - After modulation, any target color 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)

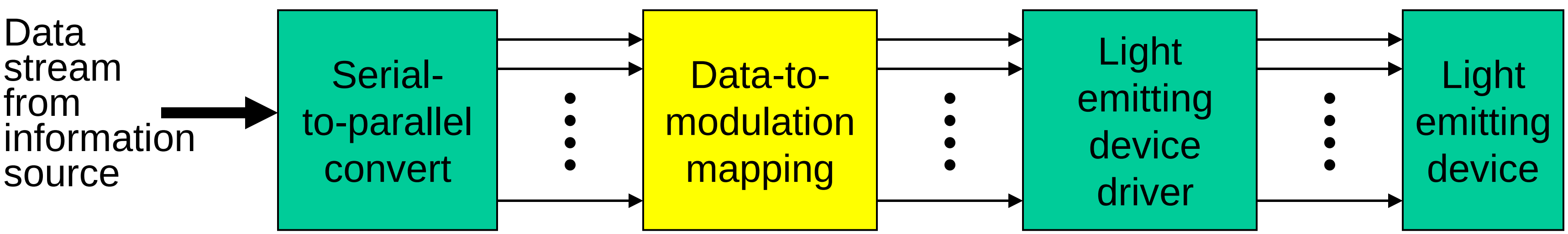
- In the modulation scheme suggested in this document, two coordinates (*x* and *y*) for a two dimensional light color space are considered.
  - *x* and *y* are designed to be orthogonal to each other to be applied for the scheme:
    - No correlation between these two.
    - Any point in a space can 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.

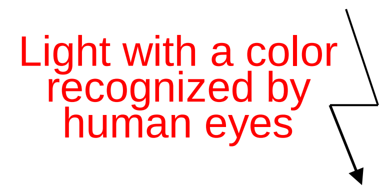
BASIC CONCEPT: MULTI COORDINATES TO REPRESENT COLORS (2)

- 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 lights 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 in general.
  - → 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.

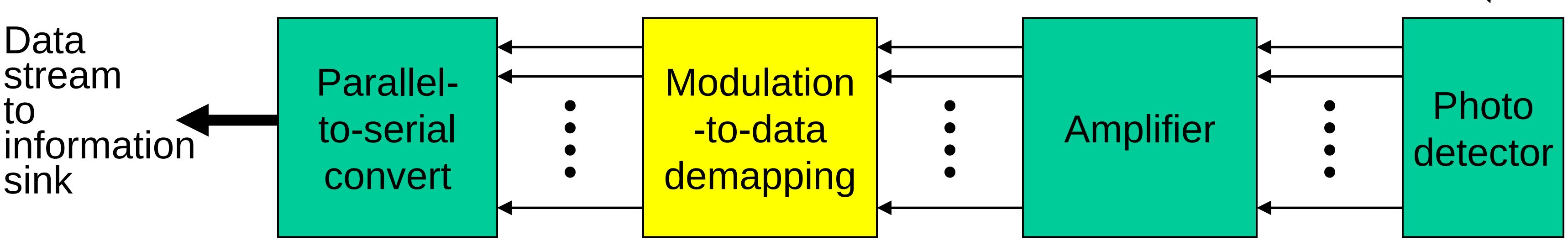
MODULATION BLOCKS

- 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.

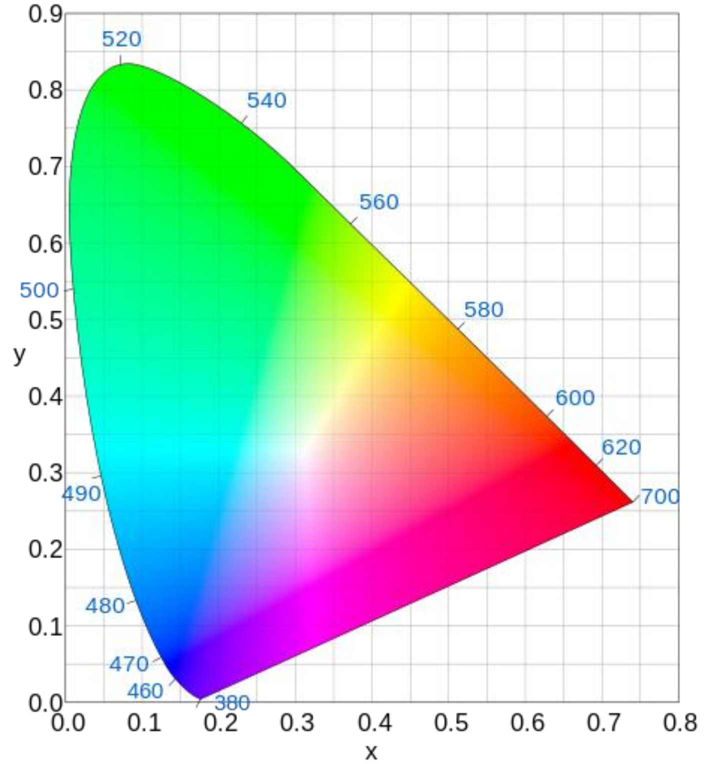
$$x = \frac{X}{X+Y+Z}$$

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

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

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

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



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.

Another fact on primary colors

- Any choice of primary colors is essentially arbitrary; for example, an early color photographic process, autochrome, typically used orange, green, and violet primaries.

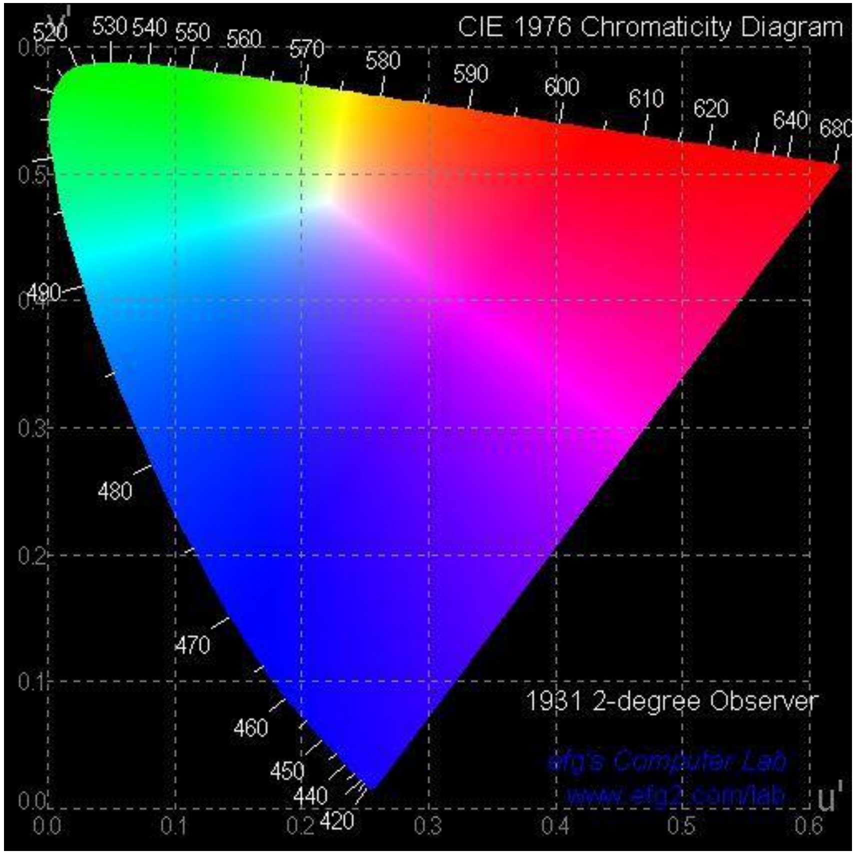
1976 CIE u'v' COLOR SPACE

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, something definitely not true in the 1931 diagram.

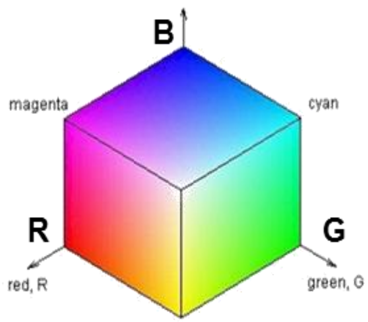
  →attempted perceptual uniformity

  →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.
- Historical inertia has won out over technical superiority: the 1976 diagram is not used as much as the original 1931 diagram.

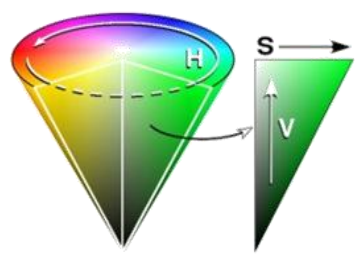


VARIOUS CONSTELLATION DIAGRAM TYPES

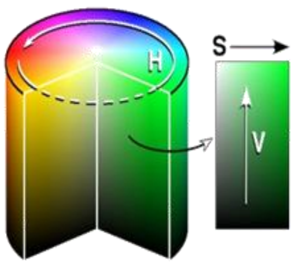
Gray



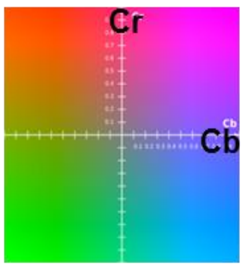
RGB



HSV(conic)

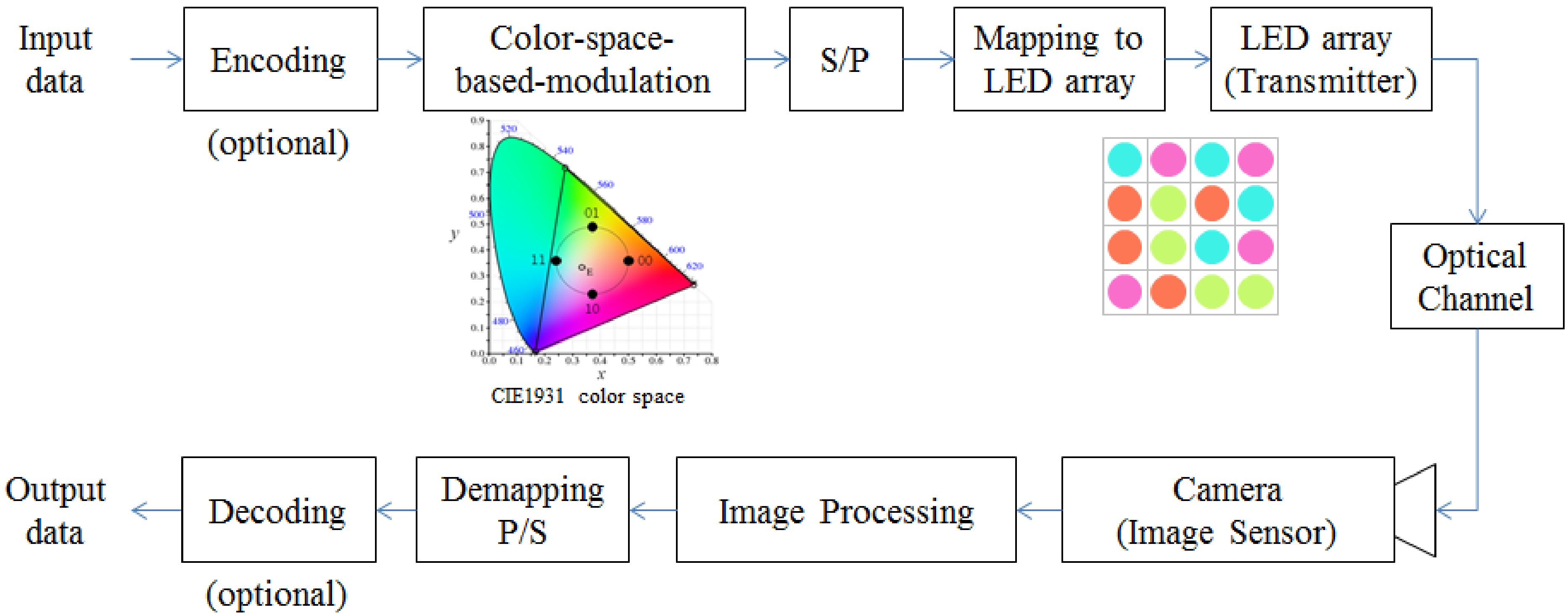


HSV(cylindric)



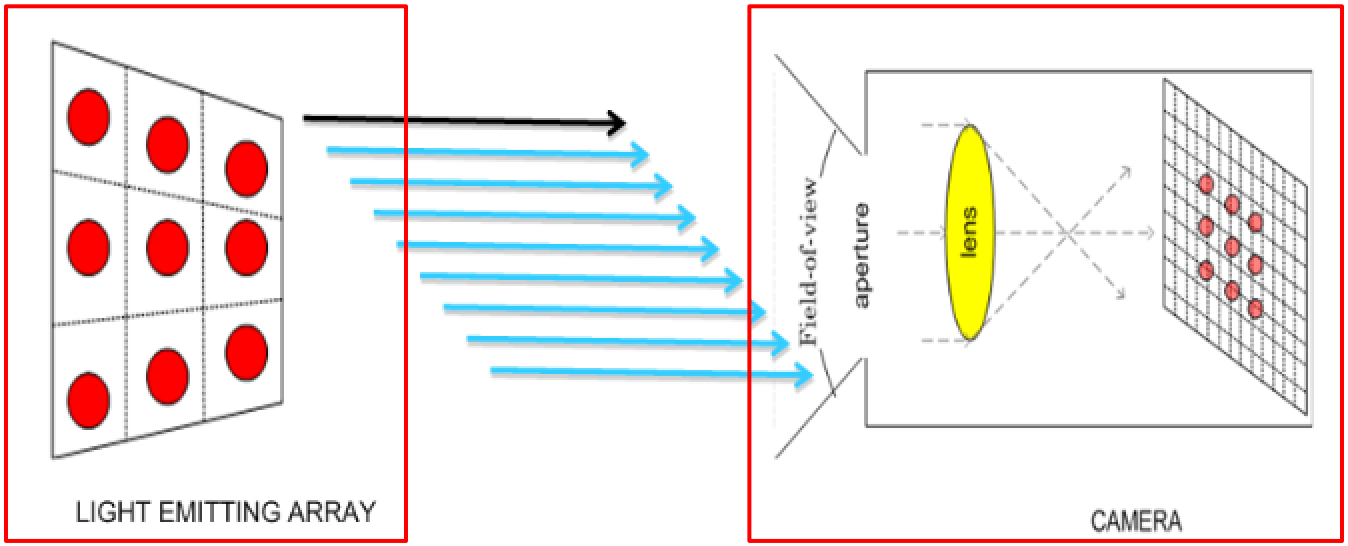
YCbCr(YUV)

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
1. Smart phone
2. Vehicle
3. CCTV

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 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 –but not uniquely for most cases. 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. One possibility is use of spectrally uncorrelated light sources or photo detectors, but it is not assumed in this document.
  - A unique color for a point in the space can be generated by mixing lights emitted from *n* light emitting devices and be detected by processing light signals detected by *k* photo detectors.

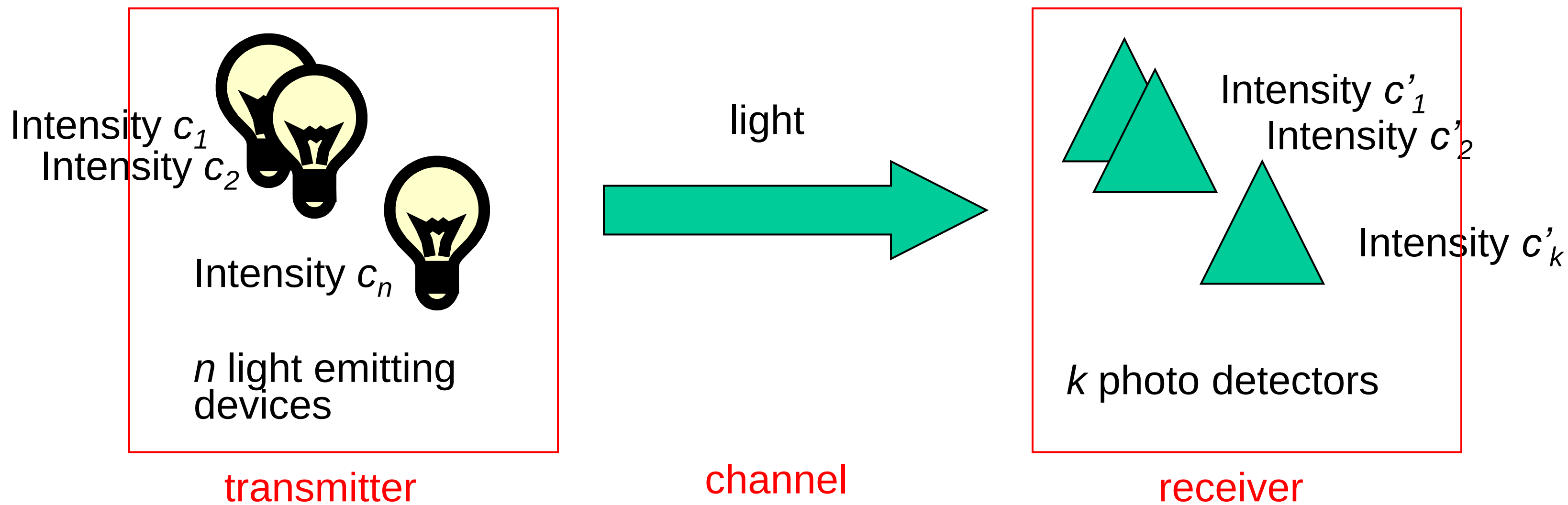
BASIC CONCEPT (2)

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, $S(\lambda)$, 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.
- Perception by Human Eyes
  - To know how human eyes react to emitted light, emitted light signal which has spectral distribution, $S(\lambda)$, 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 has spectral distribution, $S(\lambda)$, which is delivered to the detector which is characterized by its responsivity, its own spectral sensitivity, which determines the spectral characteristics and total received power to determine color detected.

BASIC CONCEPT (3)

Light Signal Delivery Model from Transmitter to Receiver Intensity



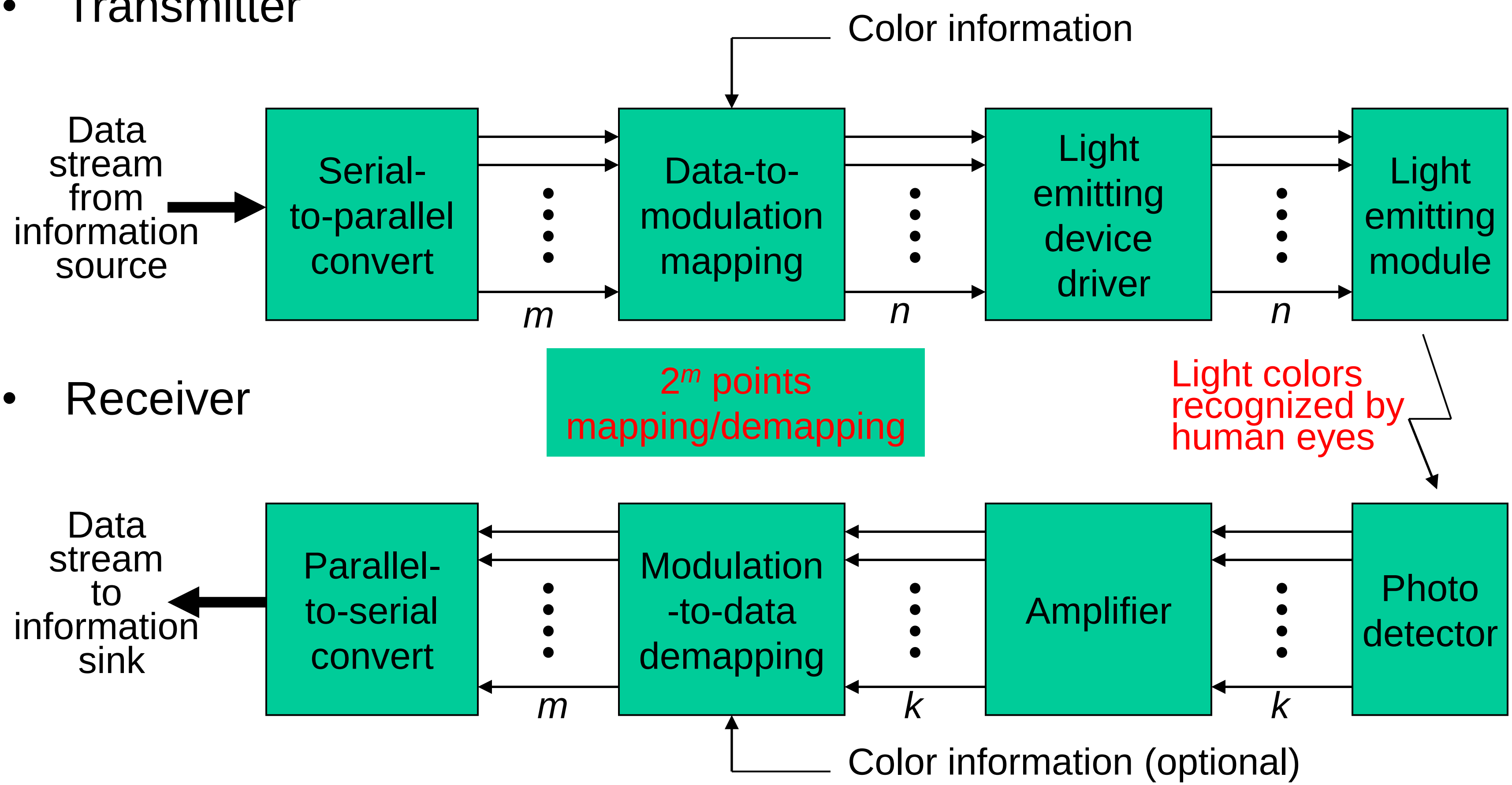
$c_{total} = c_1+c_2+\ldots+c_n$
where $c_i = \int s_i(\lambda)d\lambda$

$c'_{total} = c'_1+c'_2+\ldots+c'_k$
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

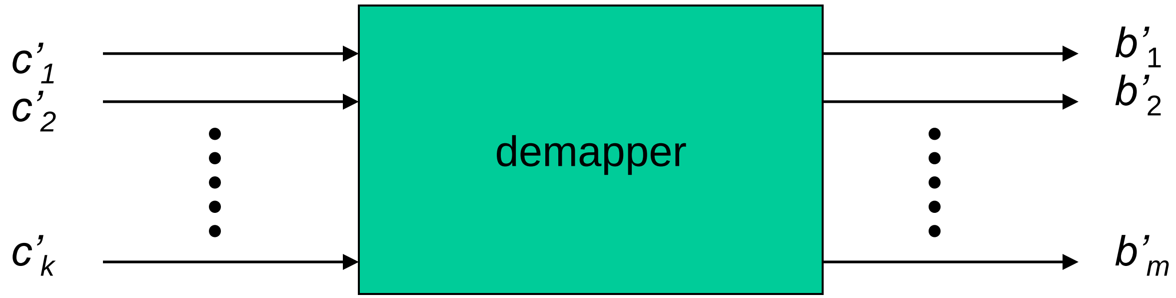
- Transmitter
- Receiver



KEY PART FOR NEW MOD: MAPPING

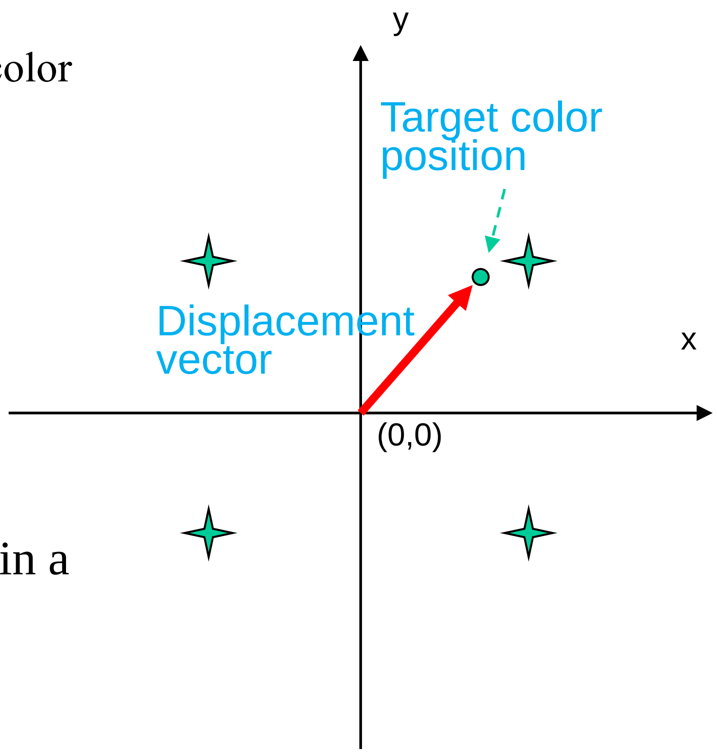
Data-to-modulation mapping (transmitter)

Modulation-to-data demapping (receiver)



GENERATION OF CONSTELLATION (1)

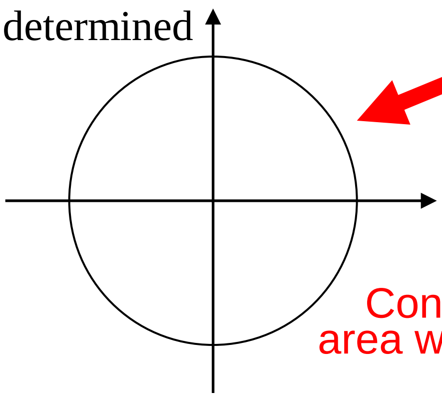
- Assumptions
  - Equi-probable data elements
  - For a fixed number of symbols' duration, color is not changed.
- Input
  - Information data: m bits → 2^m symbol elements → 2^m points
  - Color information: (x_c,y_c)
- Output
  - Constellation: (x,y)
- Two parameters considered to pick points in a light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

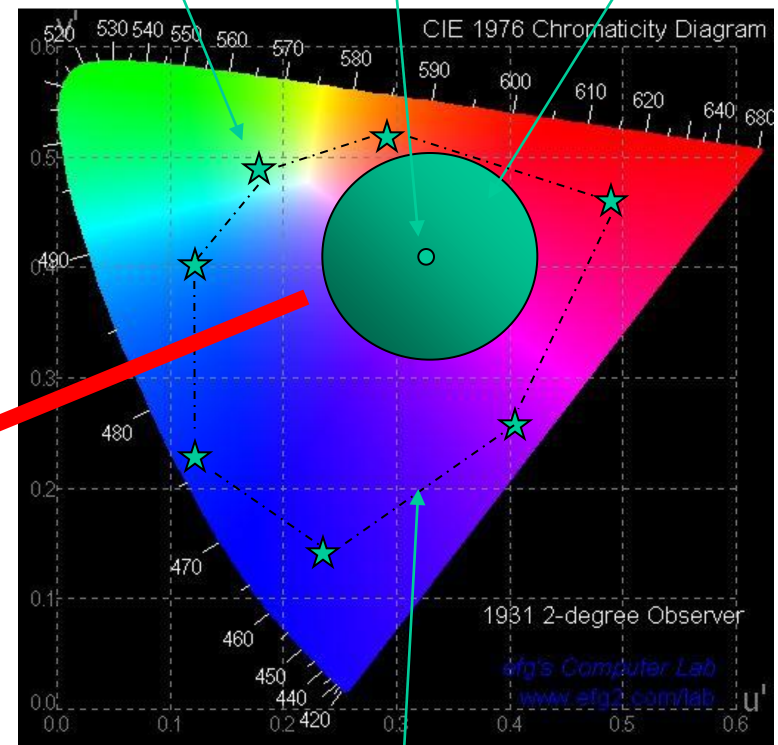


GENERATION OF CONSTELLATION (2)

- Maximum area of constellation is determined by two factors:
  - Point of target color for 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



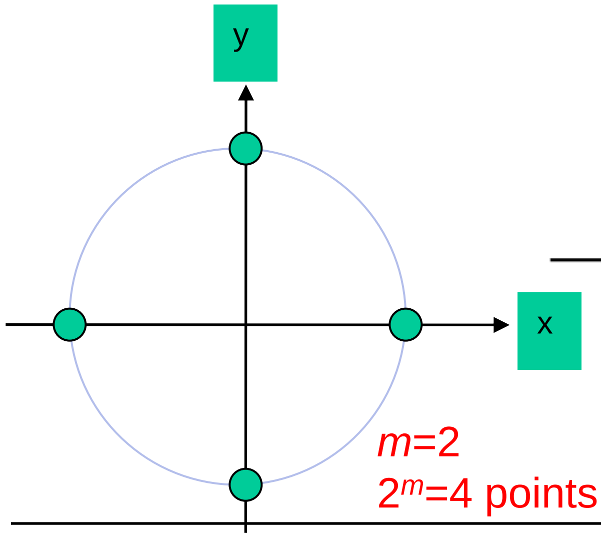


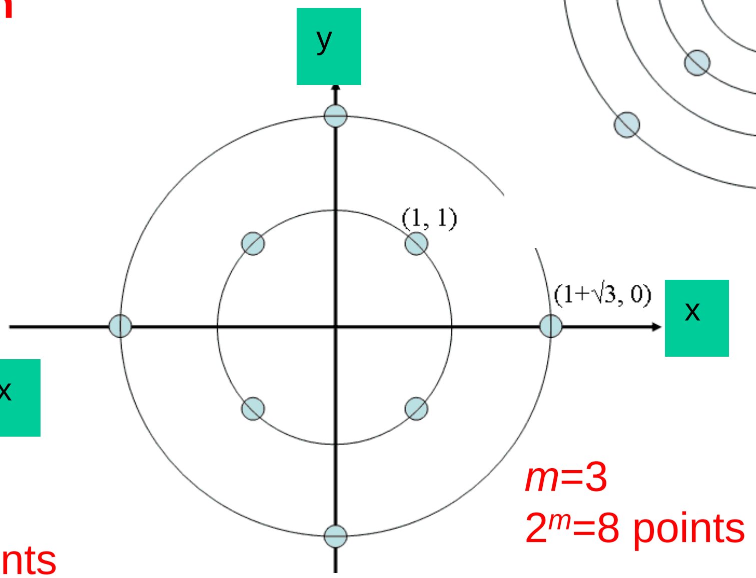
GENERATION OF CONSTELLATION (3)

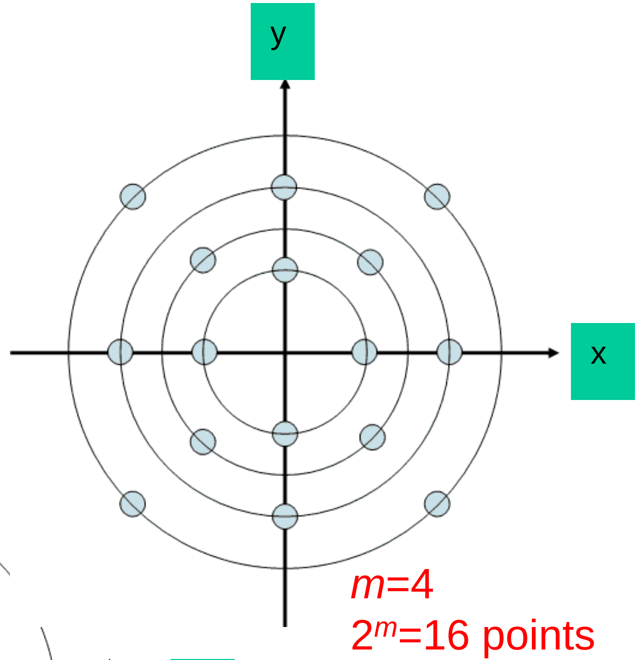
<u>Normalized constellation</u>

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





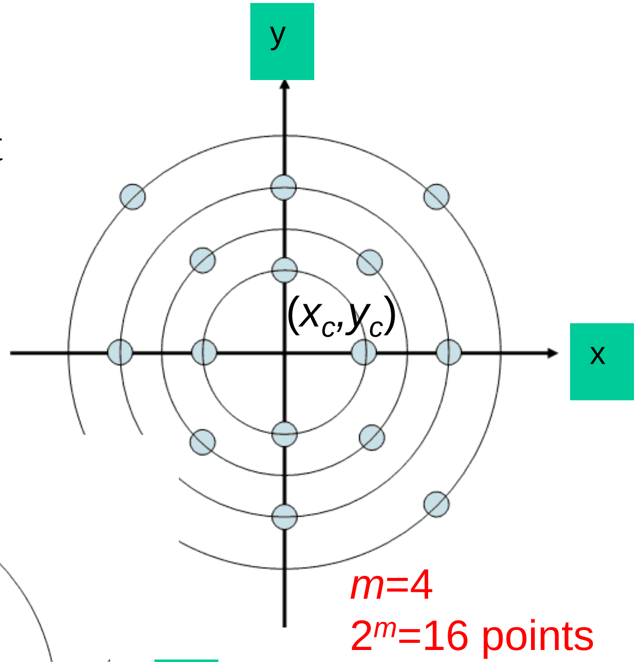


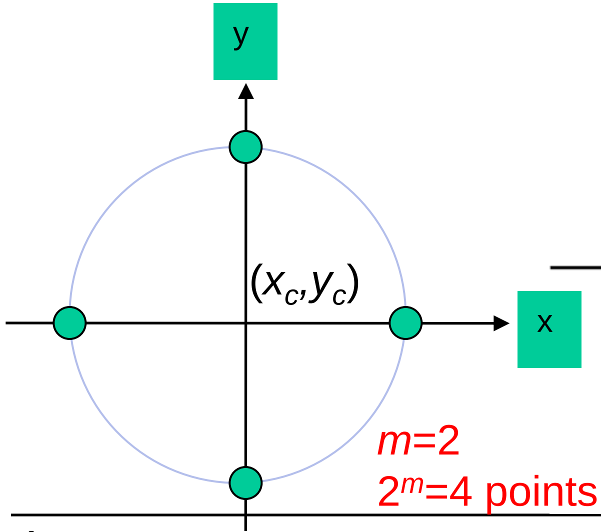
GENERATION OF CONSTELLATION (4)

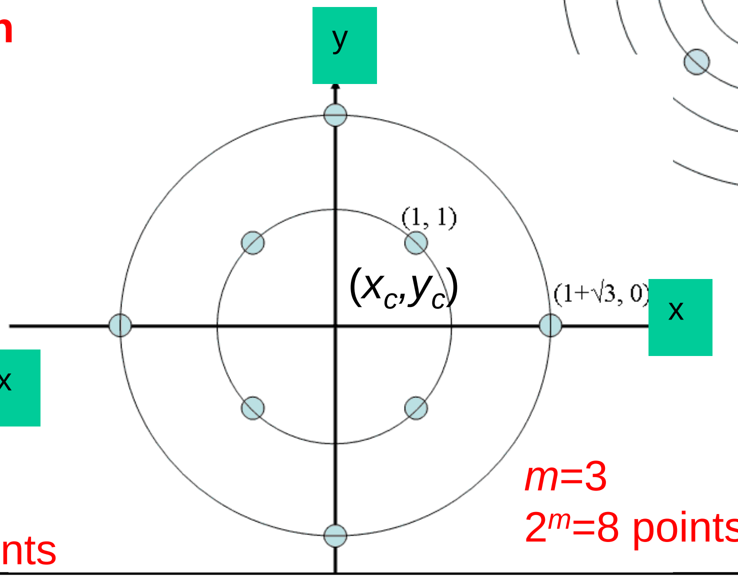
<u>Constellation scaled with the center of target color location</u>

Normalized constellation generated is shifted so that the center is located at the target color point and 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: (x,y)
  - Output: $(c_1, c_2, \ldots, c_n)$
- 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 and can get color information for each symbol received for itself or from outside.
- Input/output
  - Input: (c'_1, c'_2, . . . , c'_k): light intensities measured by photo detectors: noise added from channels to 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

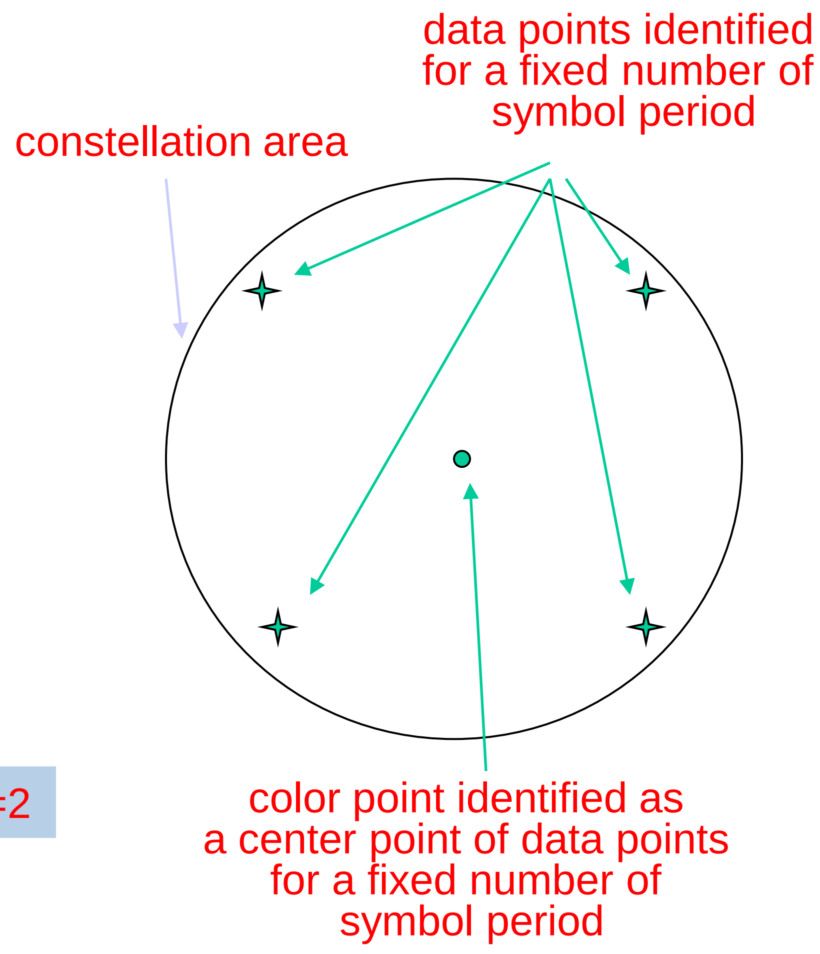
1. Using (x'_i,y'_i), i=1, 2, .., k, for all photo detectors if these values are given
2. Using spectral distributions of photo detectors if (x'_i,y'_i), i=1, 2, .., k, is not given

COLOR INFORMATION FROM CONSTELLATION

<u>How to extract color information at receiver?</u>

Two cases

1. Transmitter sends color information (*xc*,*yc*): TV signals, etc.
2. Using a fixed number of previous received symbols, color information can be extracted



For an example for *m*=2

GENERATION OF TARGET COLOR OF EACH BAND USING MULTIPLE LEDS

- Basic concept
  - If there are multiple subbands in a whole band, each subband can not be represented by a single LED: multiple LEDs should be used.
  - If 8 bands exist, eight different LEDs can be used by assigning an LED for each band. This is not a usual and most efficient case. The best way is that by using a fixed number of LEDs all bands can be covered. It can be realized using a target color generation method applied in this New Modulation.

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?

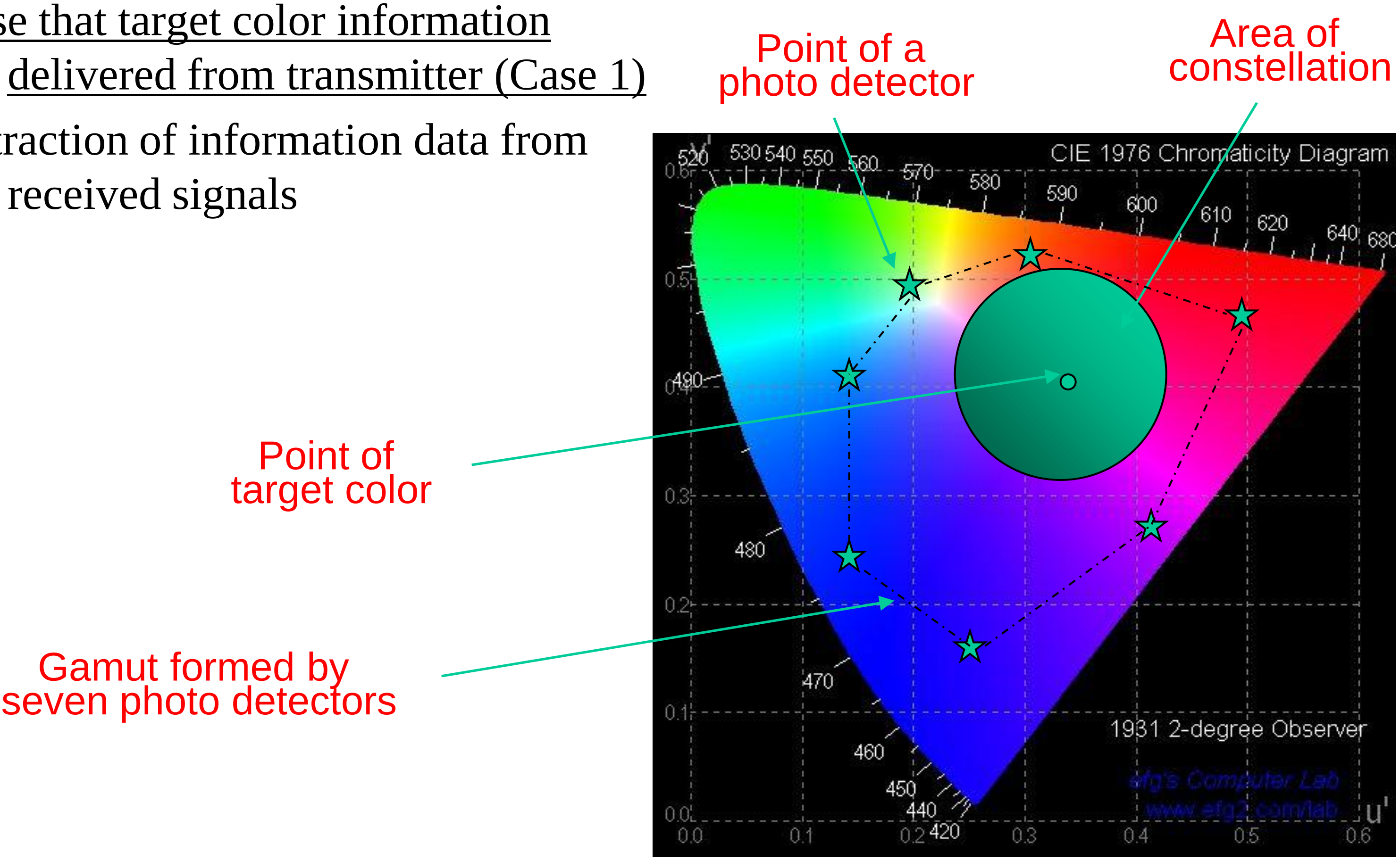
How to get constellation area at receiver?

Some cases can be considered:

1. Periodically 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 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



WHY NEW MODULATION ? MOTIVATION TO CSM (1)

- Not affected by light intensity: 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: independent of colors
  - Free from colors of lights to be sent: independent of colors of light signals
  - Any target colors generated for human eyes; signals detected by PDs
- **Progressive modulation can be achieved without any serious burden**
  - Lower to higher data rates can be achieved with a common constellation (scheme) corresponding to various applications
  - Varying number of points in a constellation and symbol periods
    - Lowest data rate for remote controlling: 2-CSM, 1 symbol/4 symbol periods→ 1/4 bit/symbol period → 40 Mbps
    - Highest data rate for file transfer: 64-CSM, 1 symbol/1 period → 6 bits/symbol period → 1 Gbps

WHY NEW MODULATION ? MOTIVATION TO CSM (2)

- Adaptive to various data rates and colors
- 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)	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 NEW MODULATION ?
MOTIVATION TO CSM (3)

- With peak transmit power fixed,
  - Higher average transmit power
  - Longer range
  - Lower BER

  are more desirable.
- New Modulation (NM),
  - should not depend on the color transmitted
    - **Self identification of colors of light signals detected**
  - 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
    - Use full power for data representation: more power can be used for transmission for the case of confined peak power.

WHY NEW MODULATION ? MOTIVATION TO CSM (4)

- Implementation issues for transmitters and receivers
  - One light transmitter consists of more than 2 light emitting devices.
  - If it is not the case, another modulation scheme should be used.
    - If existing light sources with one light emitting device is used,

- **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**
    - **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 sources by manufacturers**
    - **A simple formula applied for intensities to data demapping for 2^m CSM**

SIMULATION RESULTS (1)

- Scenario 1 -> a)Open Office -> D1~24

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

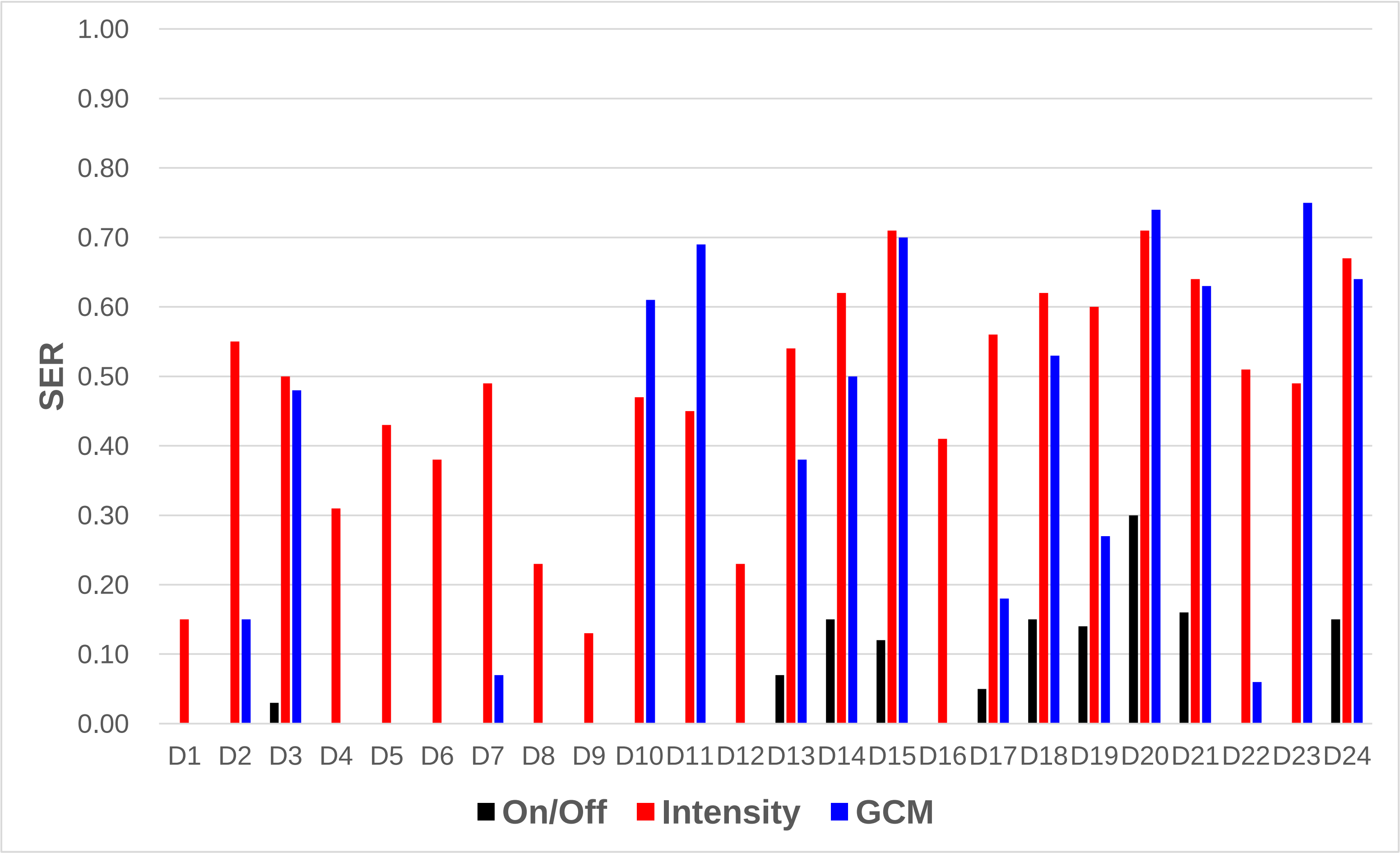
Room size	14m × 14m × 3m
Materials	Walls: Plaster, Ceiling: Plaster, Floor: Pinewood
Objects	6 desks and a chair, 6 laptops on each desk, 6 cubicles (optional) 9 human bodies
Objects specifications	Cubicles: Plaster Desk: Pinewood (Typical height of 0.85m) Chair: Pinewood Laptop: Black gloss paint Human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

SIMULATION RESULTS (2)

Performance comparison with SER for various CIRs

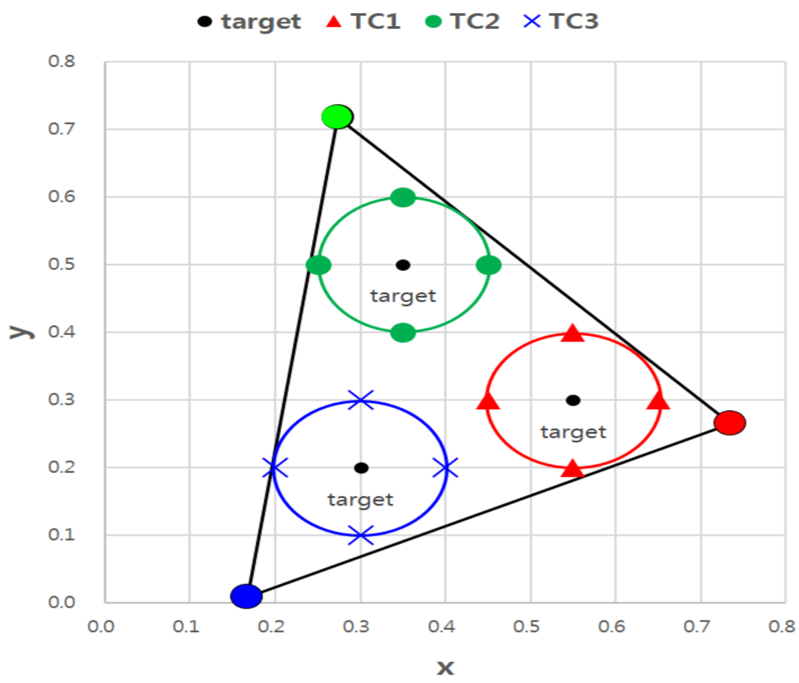
location	color	SER (Symbol Error Rate) - 100 symbols test		
		On/Off	Intensity (4 levels)	New Mod (4 symbols)
D1	blue	0.00	0.15	0.00
D2	blue	0.00	0.55	0.15
D3	blue	0.03	0.50	0.48
D4	blue	0.00	0.31	0.00
D5	blue	0.00	0.43	0.00
D6	blue	0.00	0.38	0.00
D7	blue	0.00	0.49	0.07
D8	blue	0.00	0.23	0.00
D9	blue	0.00	0.13	0.00
D10	blue	0.00	0.47	0.61
D11	blue	0.00	0.45	0.69
D12	blue	0.00	0.23	0.00
D13	red	0.07	0.54	0.38
D14	red	0.15	0.62	0.50
D15	red	0.12	0.71	0.70
D16	red	0.00	0.41	0.00
D17	red	0.05	0.56	0.18
D18	red	0.15	0.62	0.53
D19	green	0.14	0.60	0.27
D20	green	0.30	0.71	0.74
D21	green	0.16	0.64	0.63
D22	green	0.00	0.51	0.06
D23	green	0.00	0.49	0.75
D24	green	0.15	0.67	0.64

SIMULATION RESULTS (3)

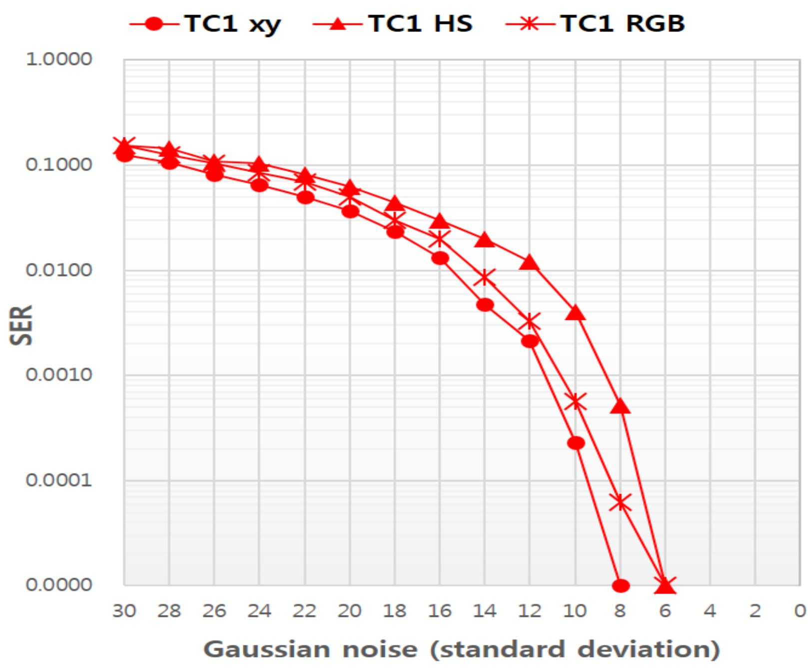


SER COMPARISON ON COLOR MODELS

constellation diagram

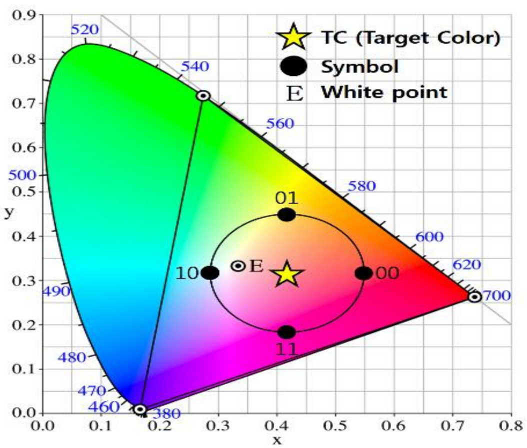


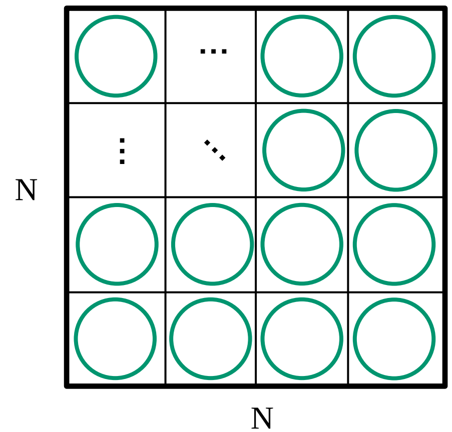
SER graph (TC1)

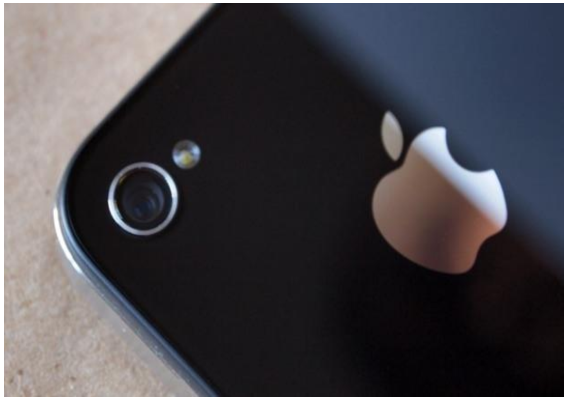


- **Symbol decision method in receiver.**
  1. x, y decision in CIE1931
  2. H, S decision in HSV model
  3. R, G, B decision in RGB model

DATA RATES ACHIEVED







▪ **Encoding** Using m(=2^n) symbols -> n [bits/symbol]	▪ **LED Array size** N x N = N^2 [symbol]	▪ **Camera frame rate** F [fps]

Data rate = n x N^2 x F [bps]

CONCLUSIONS

- New color space modulation scheme proposed has many advantages
  - Independent of brightness control
    - Not to be affected by brightness control.
  - Dependency of LED characteristics
    - Modulation technique applied is not dependent on technical characteristics of LED or other light sources deployed.
  - Not (or negligibly) affected by background noise
  - Adaptiveness to various data speeds
  - Simple implementation

- New modulation scheme proposed has better performance than other intensity modulations.