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

Submission Title: [Samsung PHY proposal to 802.15.7]
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Re: []

Abstract: Samsung PHY proposal for 802.15.7 is described in this document.

Purpose: To trigger discussion and initiate merger with other group members of TG 7.

Samsung PHY proposal to IEEE 802.15.7

Samsung Electronics

22th September

Contents

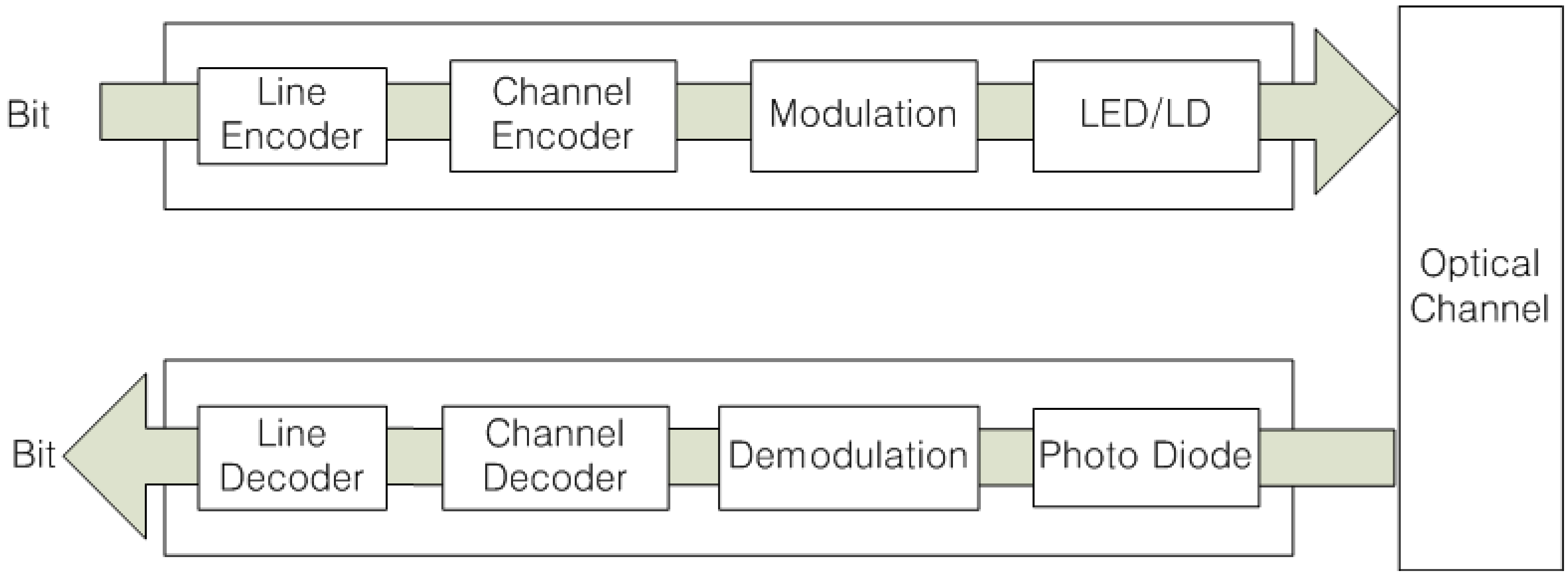
TCD(Technical Consideration Document)

- PHY considerations based on Current TCD
  - Data rate
    - data rate: 6.4Mbps~96Mbps
  - Distance
    - Short range: <= 3m
  - Device characteristic of light source
    - Divergence angle: 10 degree ~ 30 degree
  - Visibility support

Proposal scope

- P2P(Peer to Peer)
  - Full duplex (with visibility)
  - Data rate: 96Mbps
- Visible LAN
  - TDD Half duplex
  - Distance: 3m
  - Data rate: 6.4Mbps
- Information broadcasting
  - Uni-direction
  - TDD Half duplex
  - Distance: 3m
  - Data rate: 6.4Mbps

Block Diagram



Proposed data rate

Channel Coding (HHW,CC,RS)	Line coding	Sampling frequency	Uncoded data rate
2/3	0.8 (ex.8B10B)	12	6.4
1 (No channel coding)	0.8	12	9.6
2/3	0.8	48	25.6
1	0.8	48	38.4
2/3	0.8	96	51.2
1	0.8	96	76.8
2/3	0.8	120	64
1	0.8	120	96

Preamble and PHY header

Preamble	Header	Header Check Sequence	MAC payload

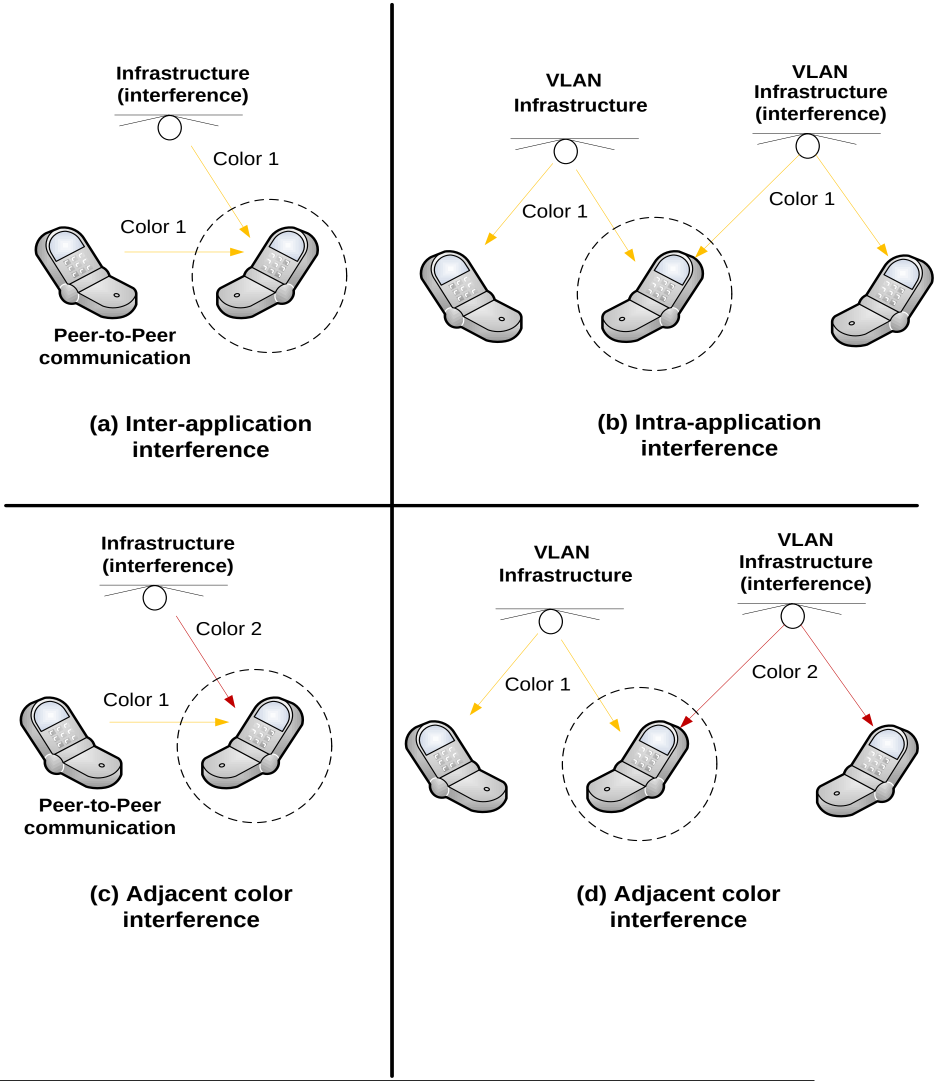
Preamble	Application
P1	P2P
P2	VLAN
P3	IB
P4	VB

PHY header fields	Explanation on use
Burst mode	Reduce preamble and IFS(Inter Frame Spacing)
Preamble	Multiple repetition of preamble for burst mode
Channel number	Colored channel
Data rate	PHY uncoded data rate
Length of MAC payload	Length upto 64KB
Alternate Mode	CCM, HHW
Reserved fields	For future extension

The information about the application is passed by the upper layers to the MAC. The MAC instructs the PHY to set the preamble for TX and for RX.

Multiple Preamble

- Problem
  - interference from ambient light sources such as sunlight, incandescent and fluorescent lamps, VLC can suffer from three types of network interference:
    - Inter-application interference (same color)
    - Intra-application interference (same color)
    - Adjacent color interference



(a) Inter-application interference

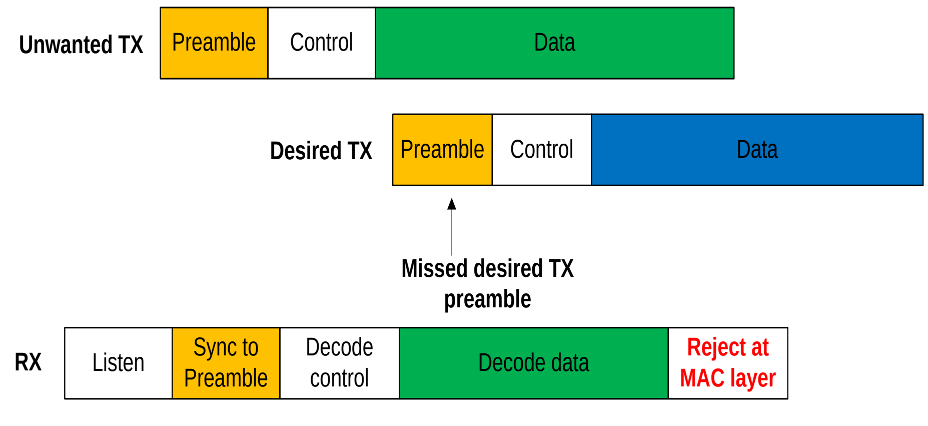
(b) Intra-application interference

(c) Adjacent color interference

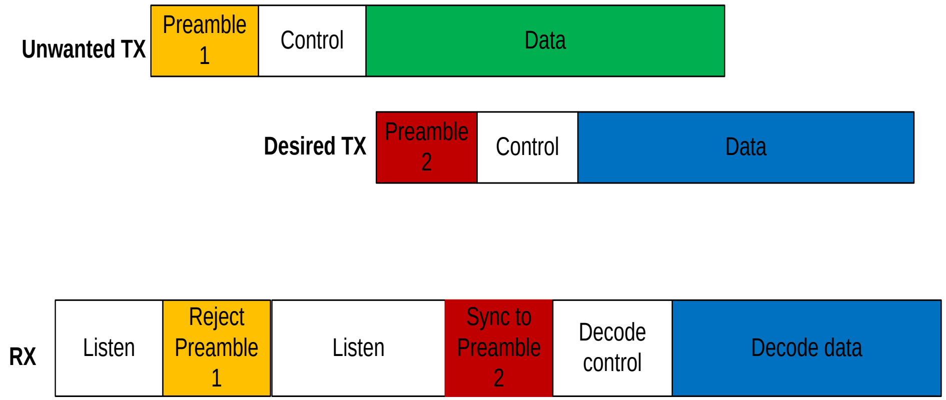
(d) Adjacent color interference

Multiple Preamble

- Benefits of multiple preamble
  - Since different preambles are used to separate different applications and/or adjacent LAN networks and/or adjacent color channels, the receiver can reject preambles of unwanted transmitters and continue listening until it sees the preamble of the desired transmitter, saving both power and having better probability of acquisition.



(a) Single preamble support



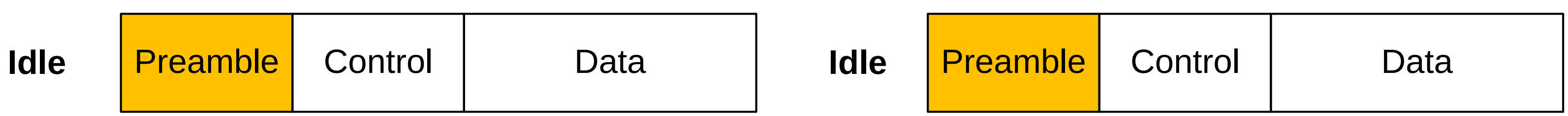
(b) Multiple preamble support

Proposed preamble design

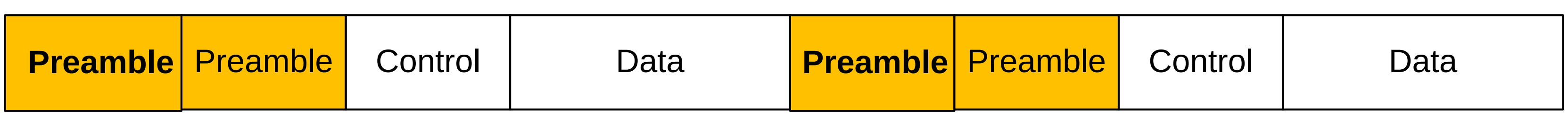
- 4 preamble sequences
  - P1 .. P4 : to distinguish applications
- 2 flip patterns per preamble
  - + and – : randomly selected to minimize interference
- 7 Cover sequences for preamble repetitions
  - 7 logical channels to separate different colors
  - Cover sequence also helps identify end of current preamble (end of preamble marker) to tell if next symbol after preamble is data or just another noisy preamble pattern
    - Higher distance means less probability of false frame sync. Distances closer to the end of the sequence are more important since the decision at the end of the frame sync sequence is crucial to determining packet detection and the initial parts of the sequence can get lost in AGC and packet detection algorithms.

Proposed preamble design

- Extended preamble for visibility and faster/better synchronization
  - preambles can also be sent as extended visibility patterns in advance of a packet transmission since they can provide visibility while simultaneously offering a chance for synchronization and additional receiver training for fast association.



(a) Default transmission



(b) Transmit extended preamble for visibility and for faster and better synchronization

Proposed Band Plan (based on CIE diagram)

Frequency band (nm)		Spectral width (nm)	Color	Proposed Code
380	450	70	pB	000
450	510	60	B, BG	001
510	560	50	G	010
560	600	40	yG,gY, Y,yO,O	011
600	650	50	rO	100
650	710	60	R	101
710	780	70	R	110
			Reserved	111

Red – popular LED for comm.

- Non-uniform distribution based on CIE diagram
- Human eye most sensitive to green color and visible LEDs are designed to match human eye sensitivity
- Provides support for up to 7 independent and parallel channels – can consider expansion to more channels

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Need for guard colors

- Many LEDs (such as white) may not support saturated colors and may transmit in multiple bands
  - Spectrum affected by leakage may be unusable
- For FDD mode, adjacent bands may be impacted by spectral leakage from own transmitter
- Significant variations in LED spectral width and peak wavelengths for different manufacturers and costs
- LED peak wavelength can change with forward current variations.

Guard colors

- Define “guard color” channels for each channel used for transmissions.
- For every channel color, we define a list of guard colors that cannot be used simultaneously for TX or RX when that channel is in use for TX due to leakage.
  - For example, white led (blue + phosphor) Color code : 001 Guard codes : 011, 100
- The criteria used for defining a guard color channel could be based on out-of-band leakage, exceeding a certain value (for example, 10 -20 dB) over the in-channel value that causes a considerable loss in receiver sensitivity in those channels.
- The guard colors are defined on a per channel basis and could be also be defined as a N-bit number with a ‘1’ in the location where the channel cannot be used.

Coding scheme for VLC

- Line coding
  - 8B10B
- Channel coding (Under investigation)
  - HHW
  - CC
  - RS
- CCM (Optional for multi color support)
  - 4CCM, 8CCM, 16CCM

Line Coding

- 8B10B
  - The 8B/10B line code that converts 8-bit to 10-bit is used in this proposal. It can help to acquire DC-balance, disparity, and clock recovery by enough state changes. It is specified in ANSI/INCITS 373: Fibre Channel Framing and Signaling Interface (FC-FS), Clause 11

Line Coding - 8B10B

- Features
  - DC balanced line code
  - Combination of 3B4B and 5B6B encoding
  - Error detection capability
  - Run length is limited to 5.
  - Disparities are constrained to be -2, 0, 2.
  - 3B4B encoding (bottom)
  - 5B6B encoding (right)

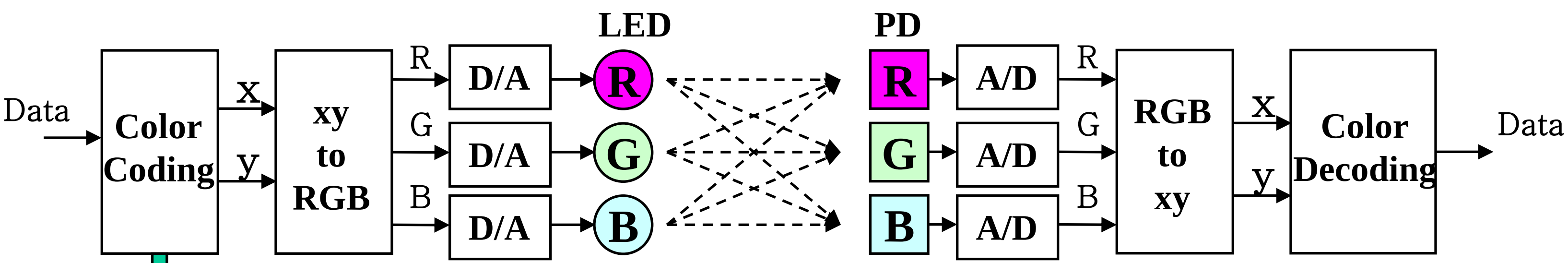
0	∞	100111 or 011000	16	∞	011011 or 100100
1	∞	011101 or 100010	17	∞	100011
2	∞	101101 or 010010	18	∞	010011
3	∞	110001	19	∞	110010
4	∞	110101 or 001010	20	∞	001011
5	∞	101001	21	∞	101010
6	∞	011001	22	∞	011010
7	∞	111000 or 000111	23	∞	111010 or 000101
8	∞	111001or 000101	24	∞	110011 or 001100
9	∞	100101	25	∞	100110
10	∞	010101	26	∞	010110
11	∞	110100	27	∞	110110 or 001001
12	∞	001101	28	∞	001110
13	∞	101100	29	∞	101110 or 010001
14	∞	011100	30	∞	011110 or 100001
15	∞	010111 or 101000	31	∞	101011 or 010100

0	∞	0100 or 1011	4	∞	0010 or 1101
1	∞	1001	5	∞	1010
2	∞	0101	6	∞	0110
3	∞	0011 or 1100	7	∞	0001 or 1110 *

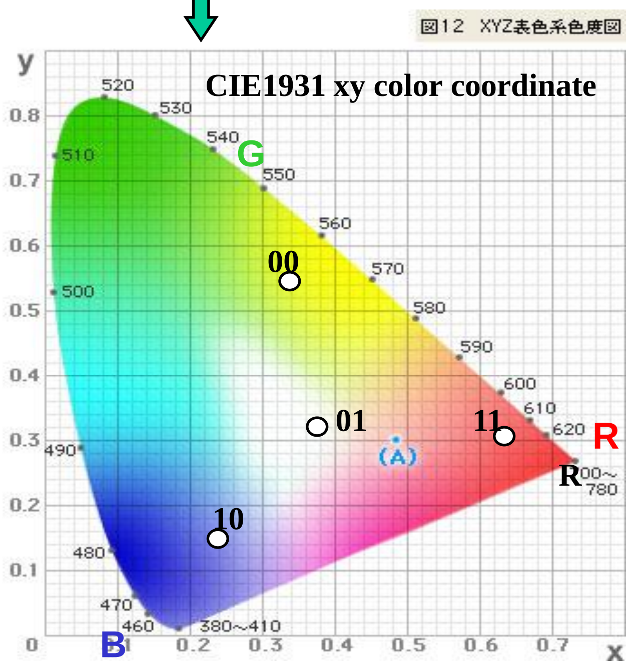
  - Example

	(RD-)	**D20.7**	**(RD+)**	**D7.1**	**(RD+)**
Violation	(RD-)	001011 0111	(RD+)	111000 1001	(RD+)
Correct	(RD-)	001011 0111	(RD+)	000111 1001	(RD+)

Modulation - What is CCM?



CCM system block diagram



4CCM symbol allocation

- **Data train is coded in the xy color coordinate.**
- **xy values are transformed into RGB values.**
- **The relation between xy and RGB is showed by following equations .(R:700nm, G:546.1nm, B:435.8nm)**

$$X = 2.7689R + 1.7517G + 1.1302B$$

$$Y = R + 4.5907G + 0.0601B$$

$$Z = 0.0565G + 5.5943B$$

$$x = X/(X+Y+Z)$$

$$y = Y/(X+Y+Z)$$

- **CCM symbols are provided as the visible colors which are made by RGB light sources.**
- **The information is transmitted as the intensity ratio among RGB.**

PHY header for CCM

Preamble	Header	Header Check Sequence	CE Sequence	MAC payload

Preamble	Application
P1	P2P
P2	VLAN
P3	IB
P4	VB

PHY header fields	Explanation on use
Burst mode	Reduce preamble and IFS
Preamble	Multiple repetition of preamble for burst mode
Channel number	Colored channel
Data rate	PHY uncoded data rate
Length of MAC payload	Length upto 64KB
Optional Mode	CCM, HHW
Reserved fields	For future extension

CE Sequence: 15 walsh code symbols

Proposed data rate for CCM mode

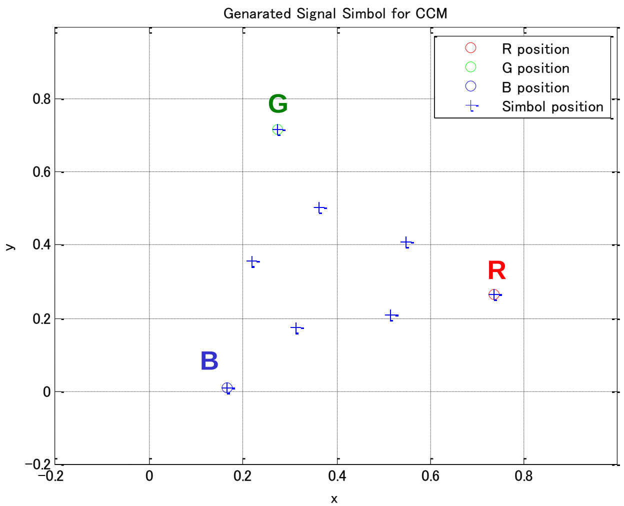
Channel coding	CCM type	Sampling Frequency 4x	Uncoded data rate
2/3	4 CCM	24	8
1 (No channel coding)	4 CCM	24	12
2/3	8 CCM	48	24
1	8 CCM	48	36
2/3	8 CCM	96	48
1	8 CCM	96	72
2/3	16 CCM	96	64
1	16 CCM	96	96

Why CCM?

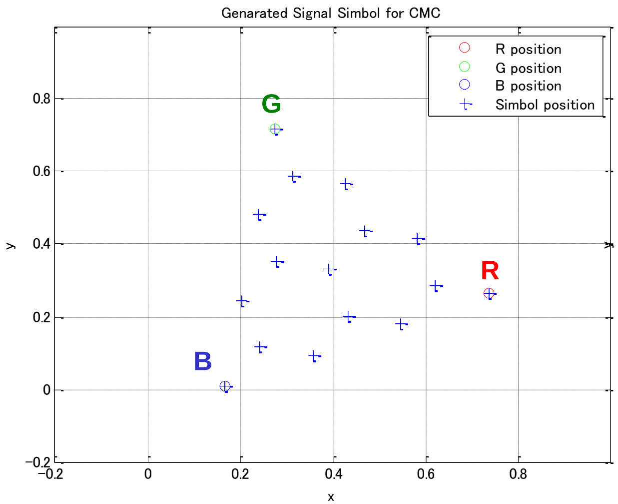
- WDM (RGB 3 colors)
  - Transmit data is distributed to RGB channels
  - The channels are decided by the wave length
    → The connectivity is depend on Light Devices (LED, PD)!

- CCM
  - Transmit data is allocated in the color coordinate plane.
  - The channels are decided by mixed color of RGB.
    → The connectivity is guaranteed symbol allocation on the xy color coordinate!

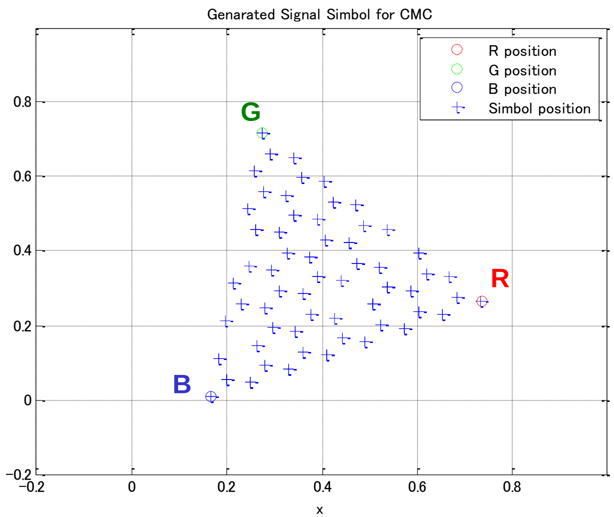
CCM symbol allocations



8 CCM (3bits/Symbol)



16 CCM (4bits/Symbol)

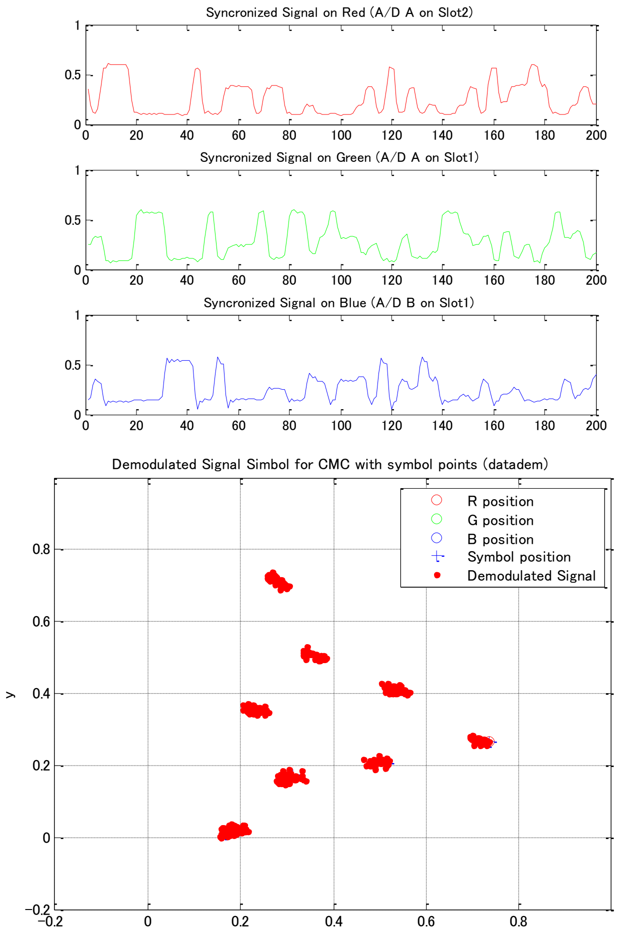


64 CCM (6bits/Symbol)

Symbol positions in xy color coordinate for CCM performance evaluation

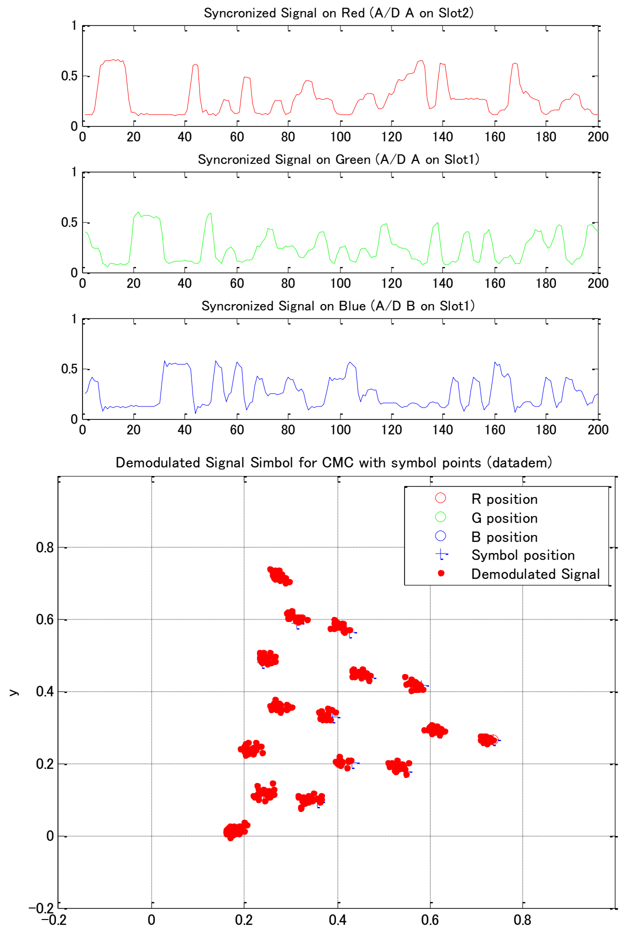
- 4CCM(2bits/Symbol) has been shown in previous page.
- Those symbol positions were decided for having same distance from adjacent symbols.

Experimental Results（25MHz/Symbol)



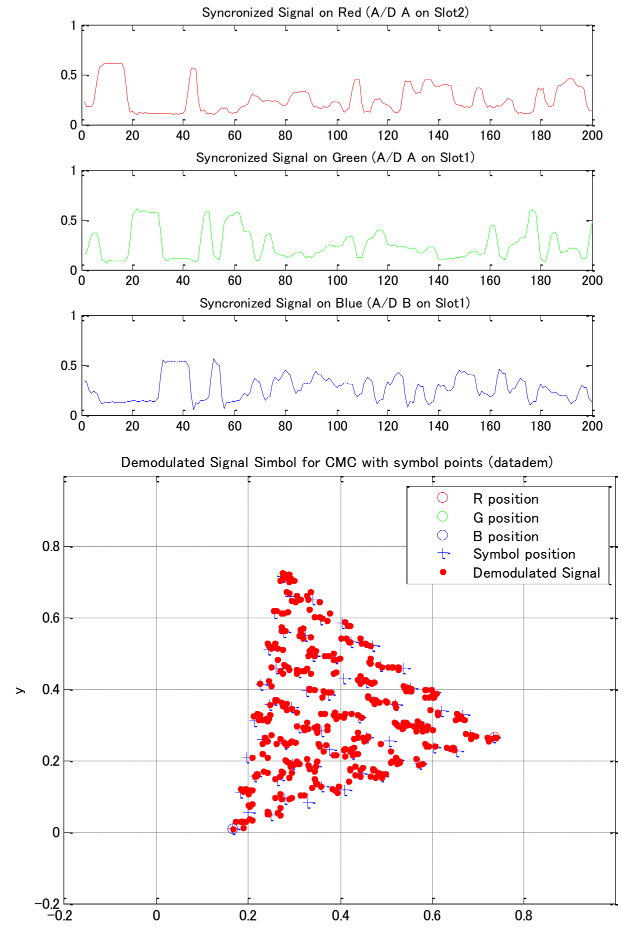
8CCM (75Mbps)

BER < 10^{-7}



16CCM (100Mbps)

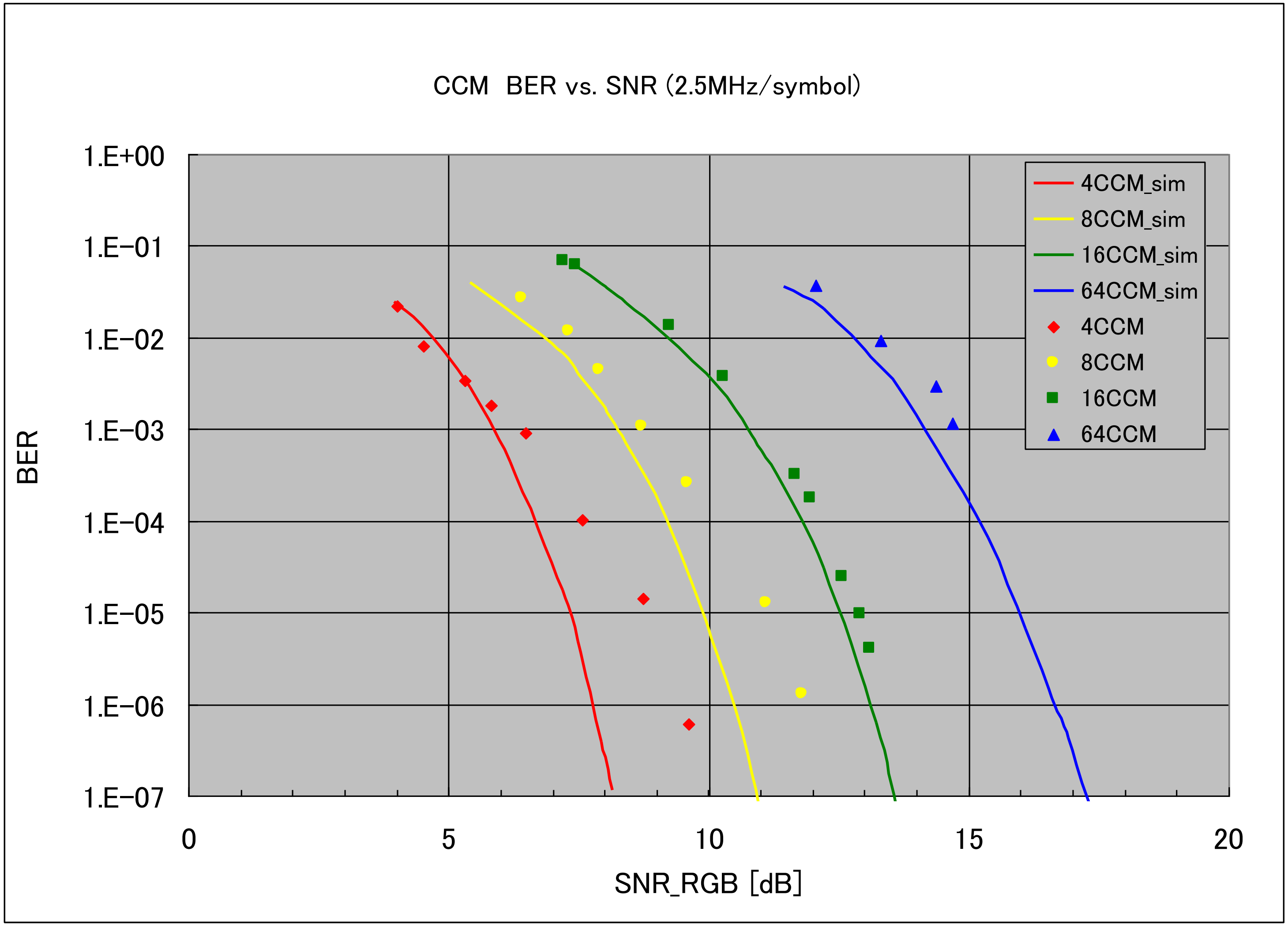
BER < 10^{-7}



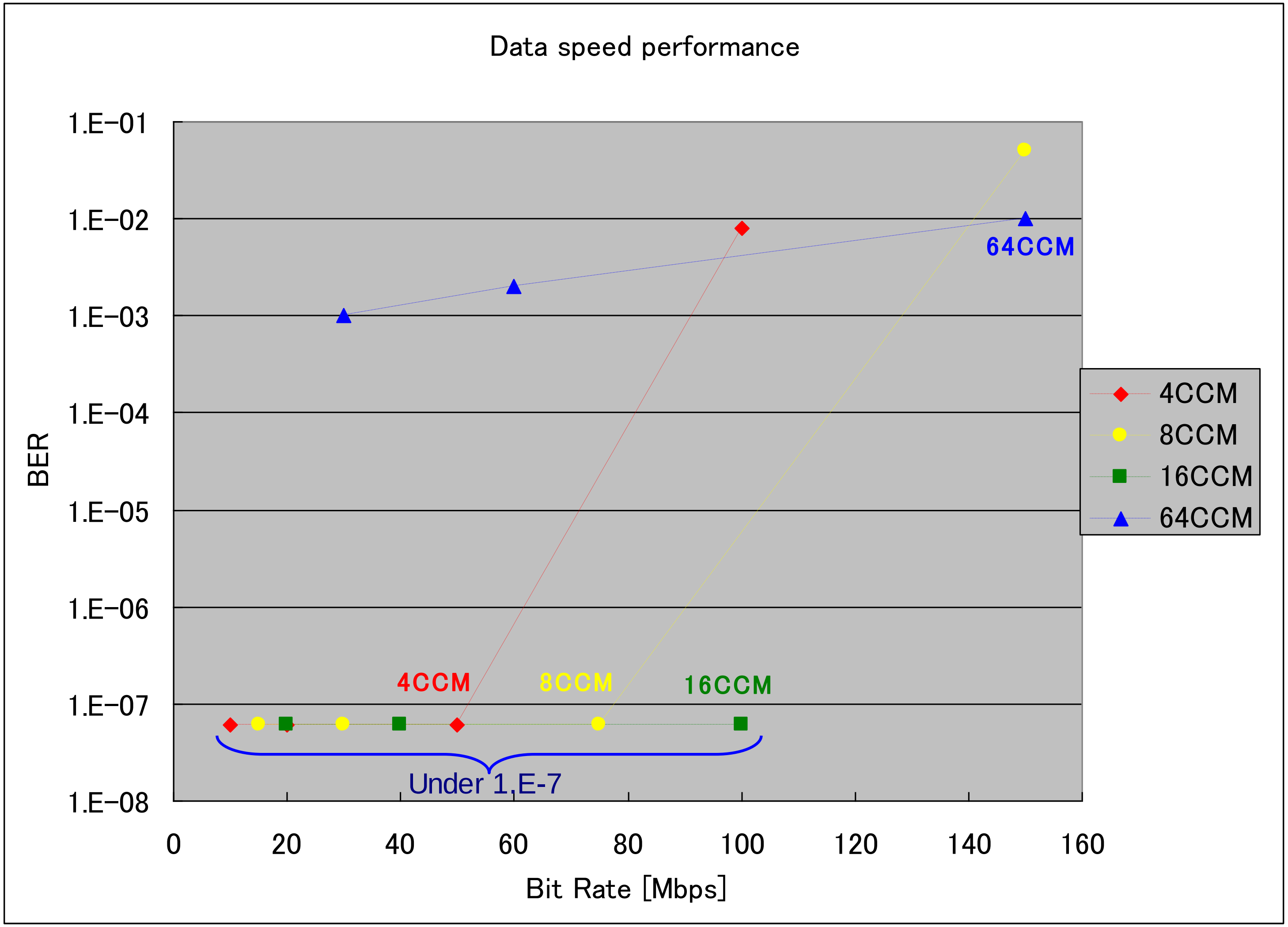
64CCM (150Mbps)

BER ≒ 10^{-2}

BER performance with random noise



BER performance vs. Bit rate

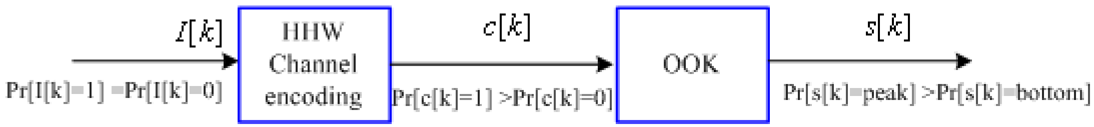


Modulation

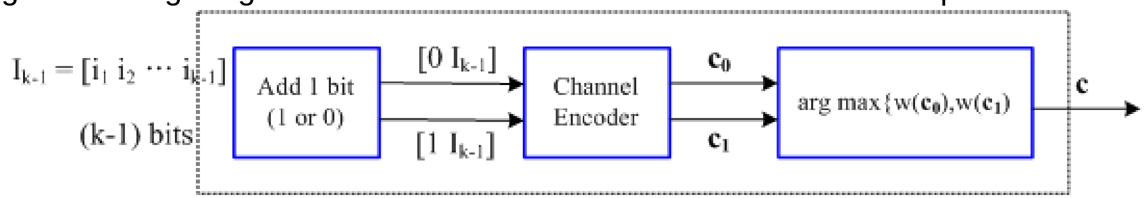
- HHW(High Hamming Weight)
  - Motivation
    - In level line code like NRZ, OOK, etc, as the appearance of 1s increases, the illumination of system is improved.
      - Ex) [0 1 1 1 0 1 1 1] → 6/8=0.75
        [0 0 1 0 0 1 0 0] → 2/8=0.25
    - In general, the occurrence of 0 and 1 is equiprobable.
  - We propose coded modulation with high density of 1's by intentionally using high Hamming weight codewords.

High Hamming Weight (HHW) Coded Modulation

- High Hamming Weight coded modulation



  - HHW channel encoding block
    - High Hamming weight codewords are selected for transmission to improve the illumination



  - Example for HHW encoding : (7,4) Hamming code

Message	Codewords	Usage
0 0 0 0	0 0 0 0 0 0 0	Unused
1 0 0 0	1 1 0 1 0 0 0	Used
0 1 0 0	0 1 1 0 1 0 0	Unused
1 1 0 0	1 0 1 1 1 0 0	Used
0 0 1 0	1 1 1 0 0 1 0	Used
1 0 1 0	0 0 1 1 0 1 0	Unused
0 1 1 0	1 0 0 0 1 1 0	Unused
1 1 1 0	0 1 0 1 1 1 0	Used
0 0 0 1	1 0 1 0 0 0 1	Unused
1 0 0 1	0 1 1 1 0 0 1	Used
0 1 0 1	1 1 0 0 1 0 1	Used
1 1 0 1	0 0 0 1 1 0 1	Unused
0 0 1 1	0 1 0 0 0 1 1	Unused
1 0 1 1	1 0 0 1 0 1 1	Used
0 1 1 1	0 0 1 0 1 1 1	Unused
1 1 1 1	1 1 1 1 1 1 1	Used

Message	Codewords
0 0 0	1 1 0 1 0 0 0
1 0 0	1 0 1 1 1 0 0
0 1 0	1 1 1 0 0 1 0
1 1 0	0 1 0 1 1 1 0
0 0 1	0 1 1 1 0 0 1
1 0 1	1 1 0 0 1 0 1
0 1 1	1 0 0 1 0 1 1
1 1 1	1 1 1 1 1 1 1

Simulation parameter set-ups

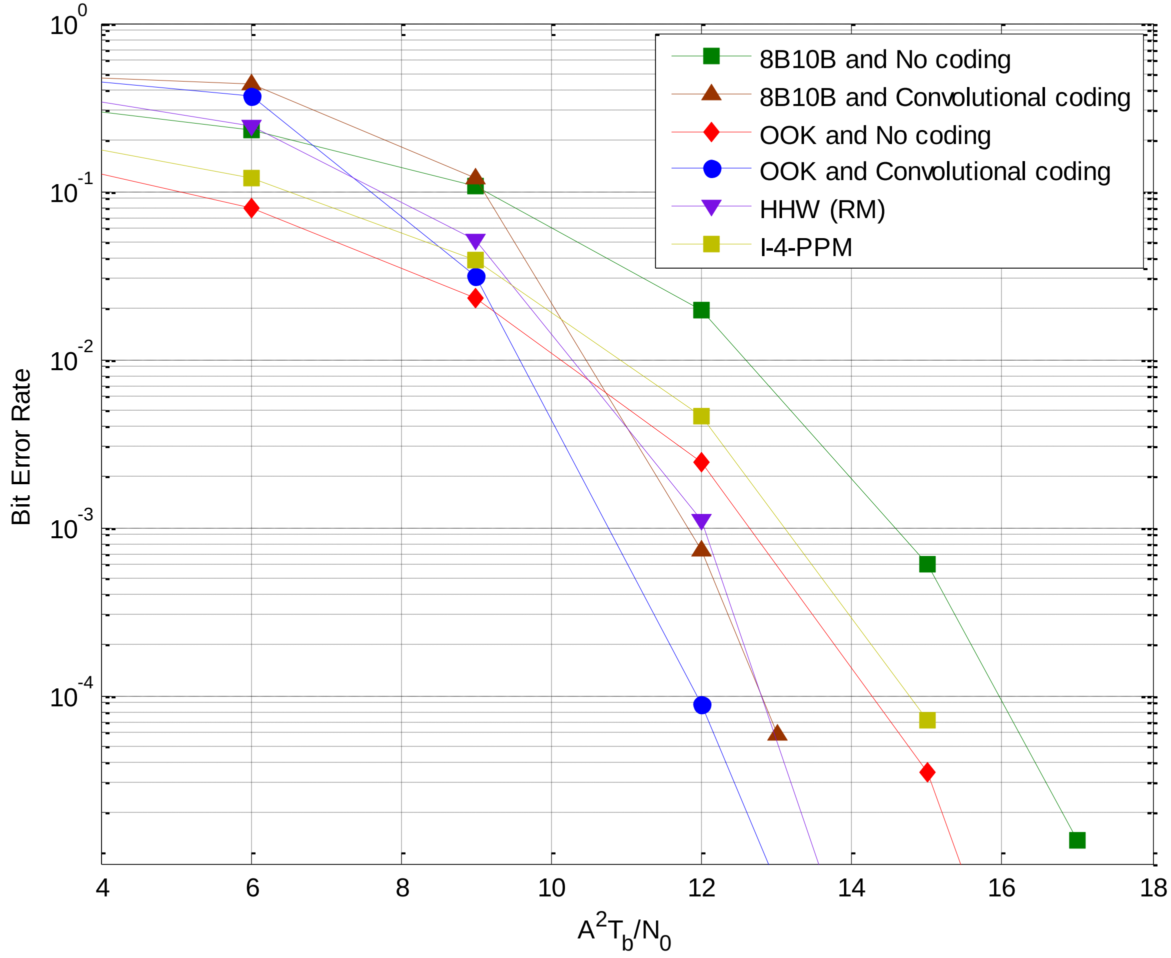
- Same peak power constraint
  - LED has a peak power limit. Maximum current of existing LEDs is strictly regulated. The peak current indicates magnitude of load on the LED.

  → Thus, we made the simulations to see the performance of various modulation schemes under the condition that peak power i.e., amplitude of each modulation is equal.
- Data rate : 10 Mbps
- Modulation and Coding scheme

Modulation	Coding
OOK	No coding
OOK	Convolutional coding (R=1/2, K=7)
8B10B	No coding
8B10B	Convolutional coding (R=1/2, K=7)
HHW Reed Muller coded modulation	OOK + Reed Muller coding (R=1/2, (16,32) code)
HHW CC coded modulation	OOK + CC (R=1/2, K=7)

[1] H. Sugiyama, S. Haruyama and M. Nakagawa, "Experimental Investigation of Modulation Method for Visible Light Communications", IEICE Transactions on Communications 2006 E89-B(12):3393-3400; doi:10.1093/ietcom/e89-b.12.3393.

HHW BER Performance



Constraint length : 7

Coding rate: 1/2

Performance Comparisons

- Average optical power normalized to peak power

Scheme	Average Optical Power
OOK	0.5
OOK+CC	0.5
I-4-PPM	0.75
8B10B	0.5
8B10B+CC	0.5
HHW RM coded modulation	0.558
HHW CC coded modulation	0.505

- BER performance with channel coding
  - HHW RM, 8B10B+CC > I-4PPM

Reference

- [1] H. Sugiyama, S. Haruyama and M. Nakagawa, “Experimental Investigation of Modulation Method for Visible Light Communications”, IEICE Transactions on Communications 2006 E89-B(12):3393-3400; doi:10.1093/ietcom/e89-b.12.3393.
- [2] L. Zeng, D. O’Brien, H. Le-Minh, K. Lee, D. Jung and Y. Oh, “Improvement of Data Rate by using Equalization in an Indoor Visible Light Communication System”, in Circuits and Systems for Communications, 2008. ICCSC 2008. 4th IEEE International Conference on, 2008, pp. 678-682.
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Appendix

Multiple Preamble

- Problem
  - It is possible that there may be leakage from adjacent color bands into the band of the chosen color, causing adjacent color interference.

Channel	Wavelength band (nm)		Spectral width (nm)	Color from CIE diagram	Proposed Code
c1	380	450	70	pB	000
c2	450	510	60	B, BG	001
c3	510	560	50	G	010
c4	560	600	40	yG,gY, Y,yO,O	011
c5	600	650	50	rO	100
c6	650	710	60	R	101
c7	710	780	70	R	110
				Reserved	111

Multiple Preamble

- Different preambles are used to separate different applications

Preamble	Application
P1	P2P
P2	VLAN
P3	IB
P4	VB

P1: 1 1 1 1 0 1 0 1 1 0 0 1 0 0 0

P2: 0 0 1 0 1 1 1 0 1 1 1 1 1 1 0

P3: 1 0 0 1 1 0 0 0 0 0 1 0 0 1 1

P4: 0 1 0 0 0 0 1 1 0 1 0 0 1 0 1

Proposed preamble design

- Cover sequence
  - cover sequences are to be applied only to the end of the preamble repetition pattern. For example, if the preamble is being repeated 32 times, the cover sequences proposed is only applied on the last 8 repetitions.

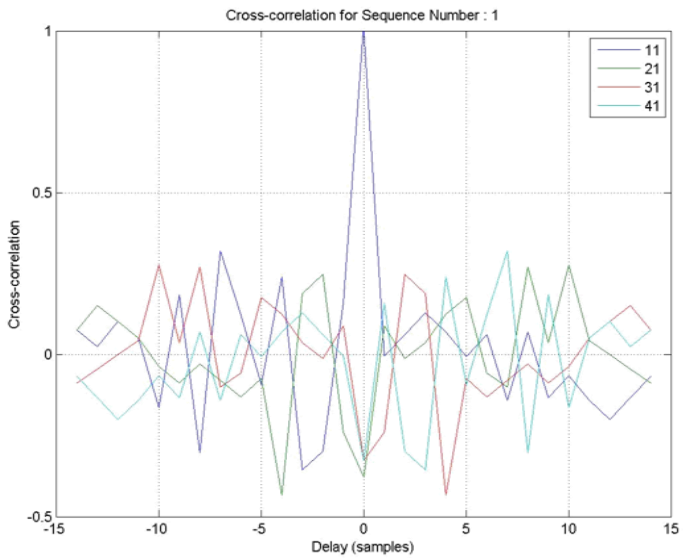
Cover sequence	**Distances**	**Sum**	**Weight**
C1: 0 0 0 1 0 1 0 1	5 1 4 1 2 1 1	15	7.79
C2: 0 0 1 0 0 1 0 1	5 3 1 3 1 1 1	15	8.09
C3: 0 0 1 0 1 0 0 1	5 3 2 3 0 1 1	15	8.23
C4: 0 0 1 0 1 0 1 0	6 1 4 1 2 1 0	15	8.65
C5: 0 1 0 0 1 0 1 0	6 2 2 3 0 2 0	15	8.75
C6: 0 1 0 1 0 0 1 0	6 2 2 3 0 2 0	15	8.75
C7: 0 1 0 1 0 1 0 1	7 0 5 0 3 0 1	16	9.41

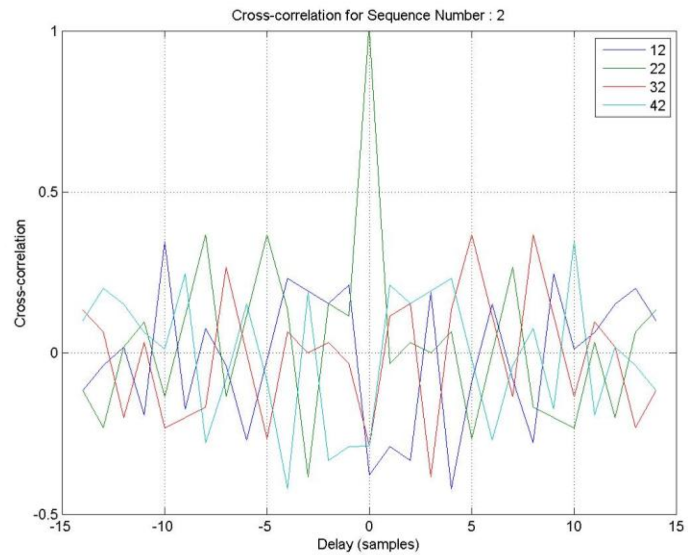
Multiple Preamble

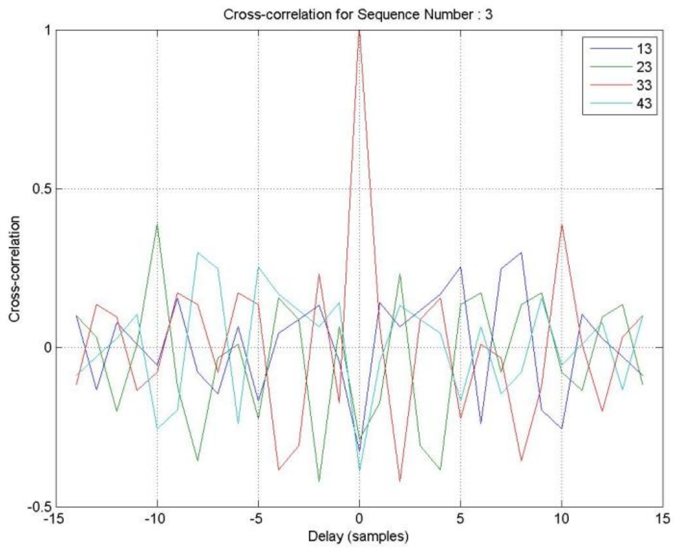
- "flipped" preamble patterns to distinguish within an application type (intra-application separation).
  - by looking at the sign of the received correlation, a determination can be made whether the sequence or its inverted pattern was transmitted

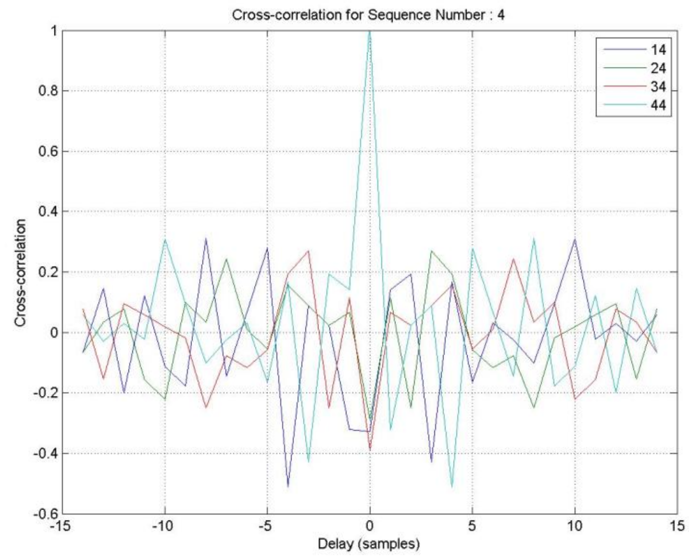
Preamble	Application
P1, ~P1	P2P
P2, ~P2	VLAN
P3, ~P3	IB
P4, ~P4	VB

Preamble simulation results

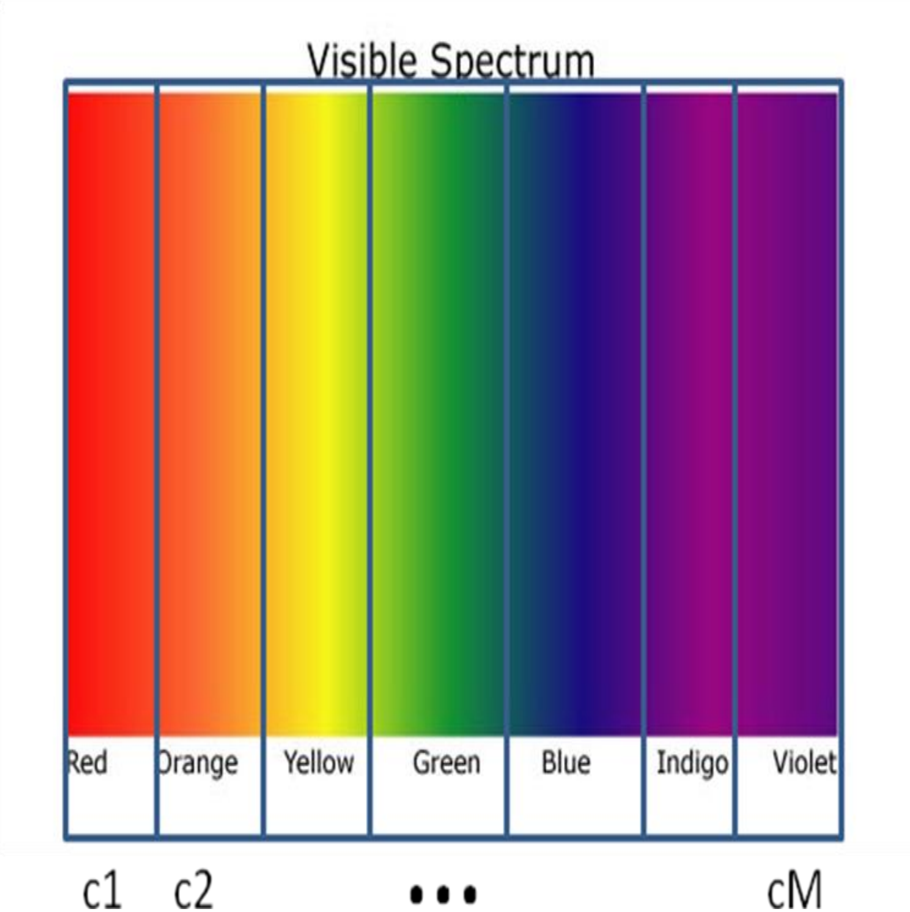


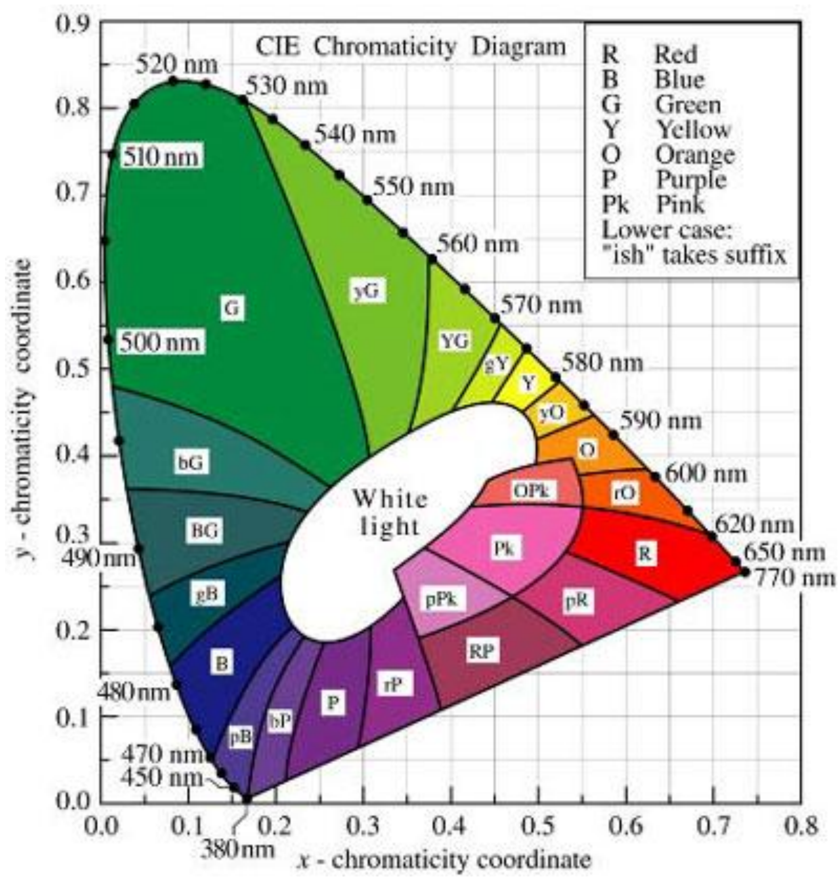






Band plan design for communicating supported channels





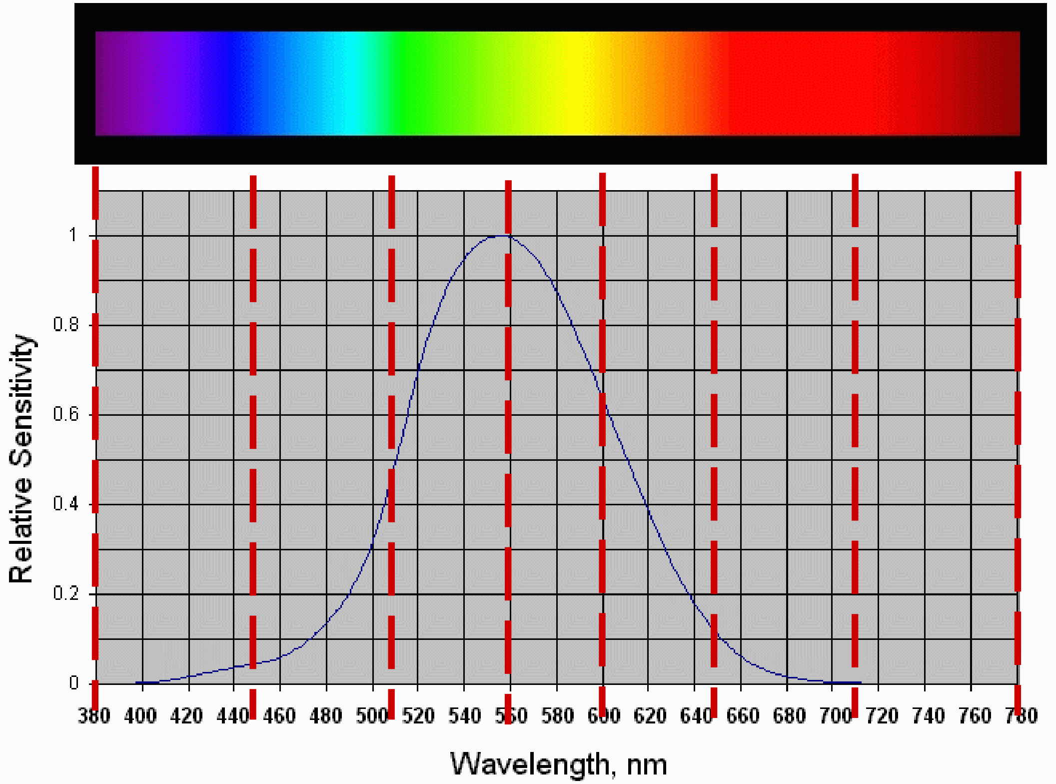
Source: http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap17/F17-03%20Chromaticity%20diagram%20(Gage).jpg

Notes from CIE diagram

- Center colors are narrower in width than outer colors.
- Human eye is more sensitive to center colors
- pB, R occupy 100~200 nm while G occupies ~ 30 nm
- LED manufacturers make LEDs depending on human color perception and not frequency band

  => Non-linear widths needed for band plan

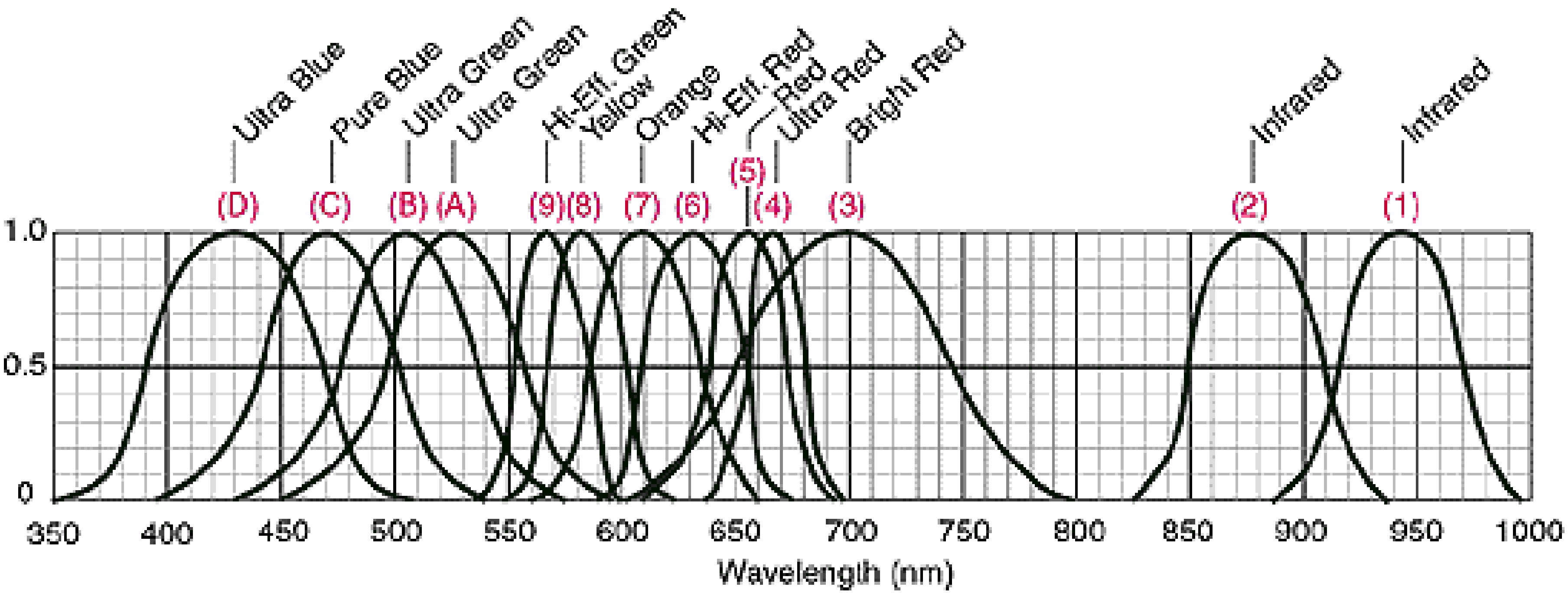
Human eye response to wavelength



Response of Human Eye Versus Wavelength
(Data from the 1988 C.I.E. Photopic Luminous Efficiency Function)

ng Electronics

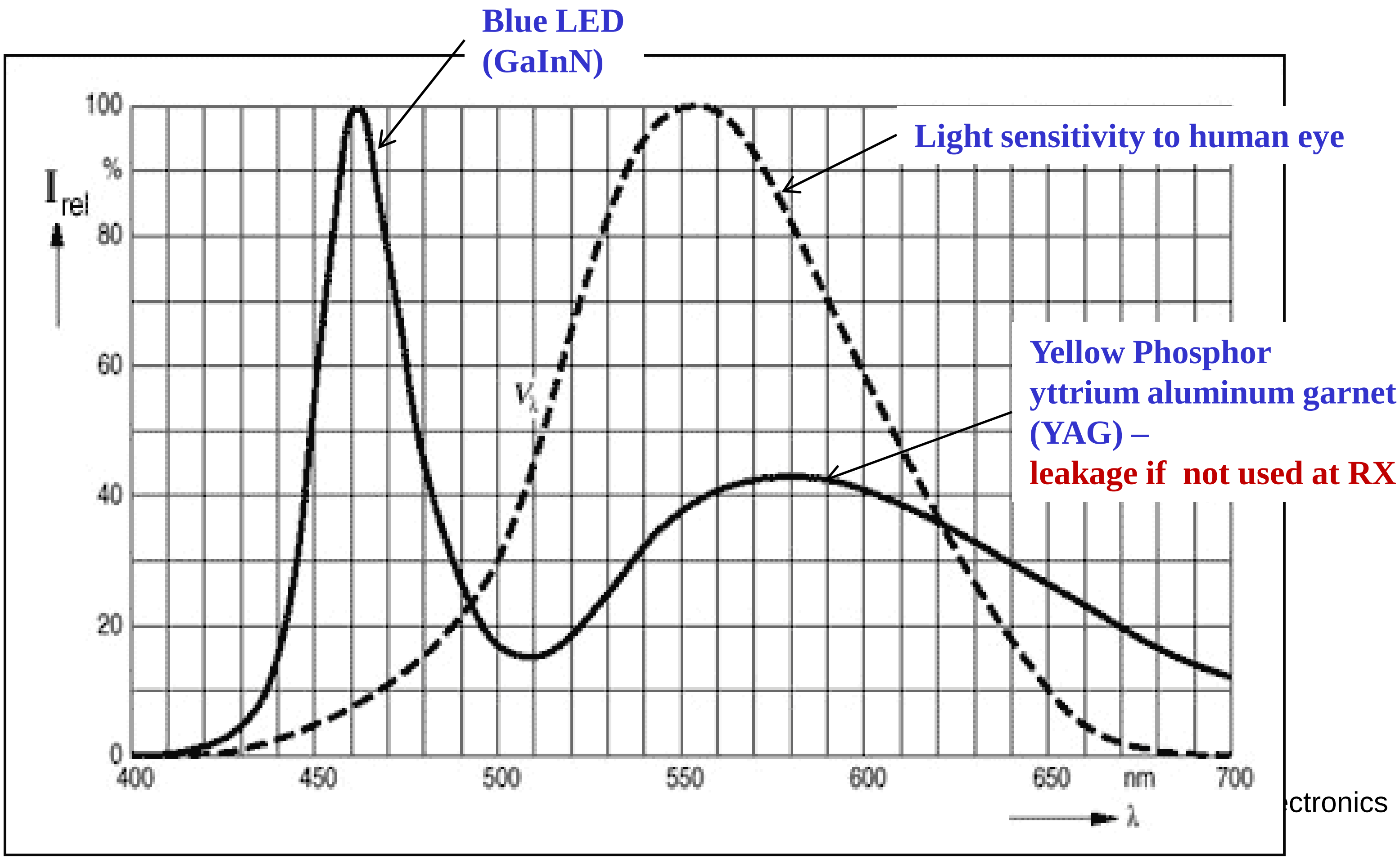
Bandplan issue:
Leakage from other LED colors



Ying Li, Samsung Electronics

Source: http://www.theledlight.com/technical3.html

White LED spectrum (Blue + Phosphor)



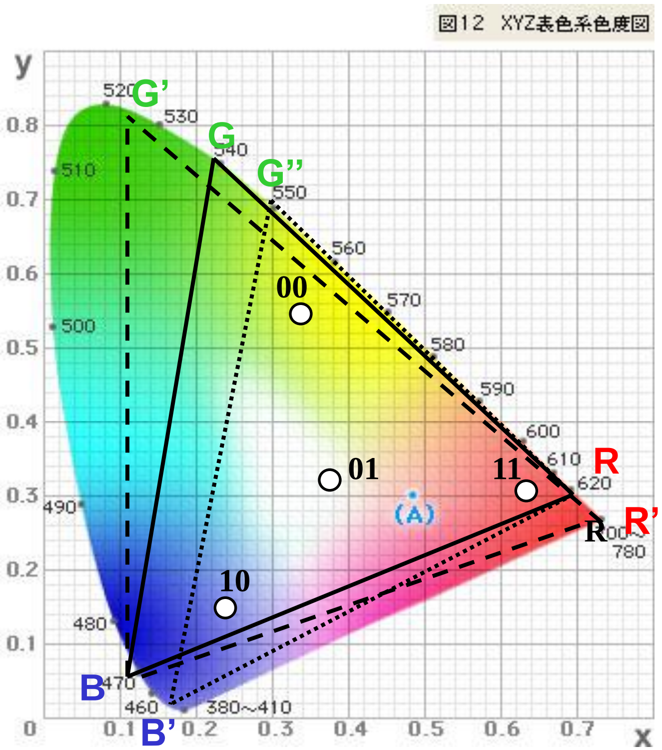
ctronics

Source: Maxim, Application Note 3070 : Standard and White LED Basics and Operation

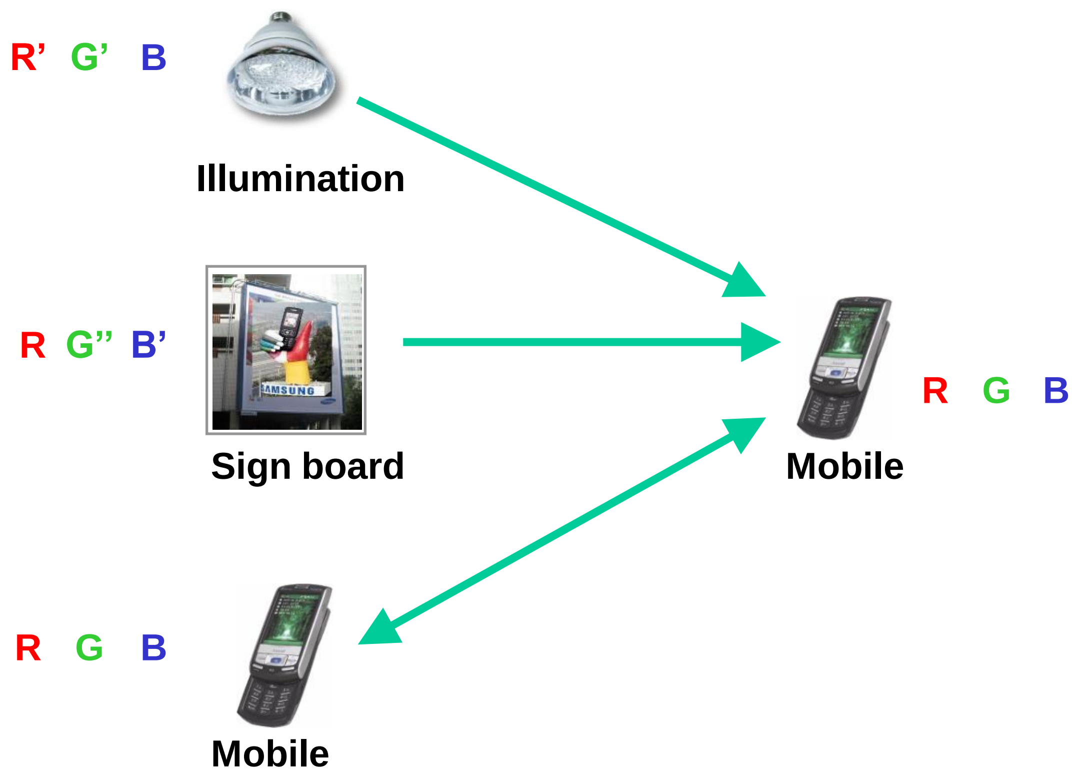
CCM Performance Table

Symbol Rate	4CCM 2bit/symbol	8CCM 3bit/symbol	16CCM 4bit/symbol
12MHz	24Mbps $<10^{-7}$	36Mbps $<10^{-7}$	48Mbps $<10^{-7}$
24MHz		72Mbps $<10^{-7}$	96Mbps $<10^{-7}$

Why CCM?



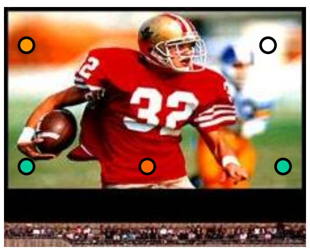
xy color coordinate



- Light source spectrum are different among the various devices.
- CCM symbols are produced by several light sources according to the color coordinate.
- CCM symbols can be reproduced by different light sensors.
- CCM guarantees the connectivity each device with xy color coordinate.
- CCM is better for VLC standardization with considering the connectivity among the different devices.

CCM Low Speed Applications

TV, PC, Sign board
Display



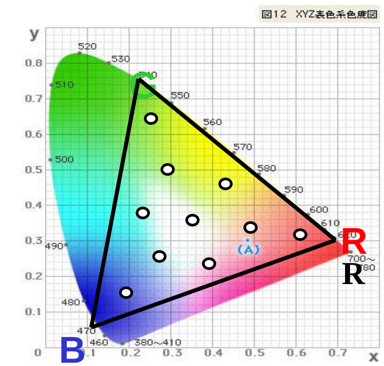
Sign board (Poster)
RGB LED

Mobile
Display

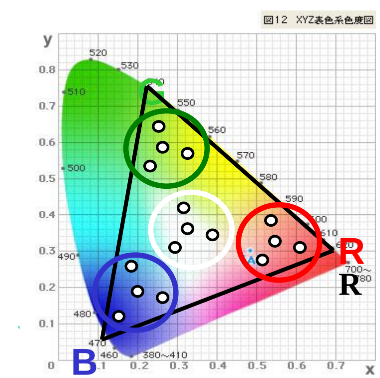
Low Speed Data
around 15kbps*

Mobile

* Data Speed Estimation
Symbol Rate:15Hz
CCM:4 bit (16 points)
SDM:16x16 points



Full Color Coding

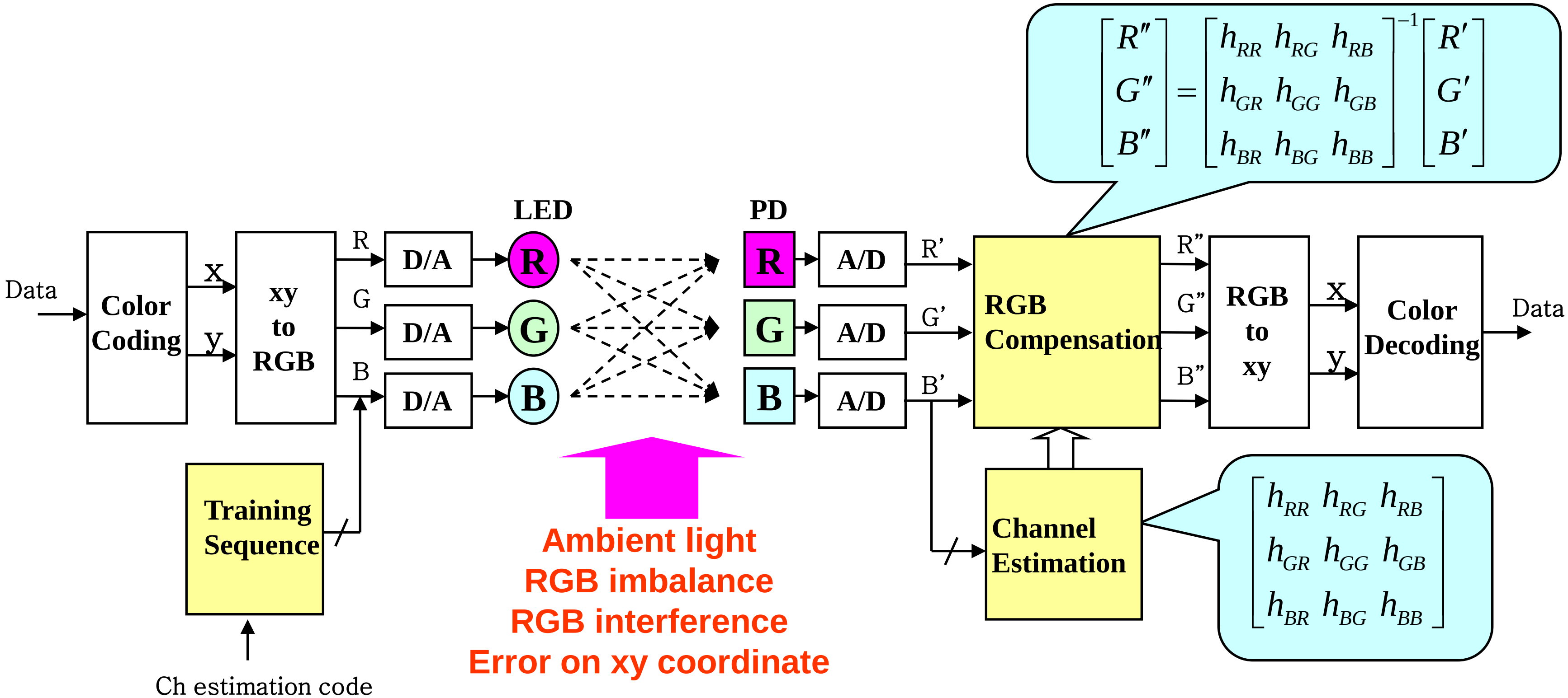


Color Offset Coding

Applications
- Special Information
- Voice streaming
- Support for disabled person
- Security

Those application are realized by existing devices and infrastructures.

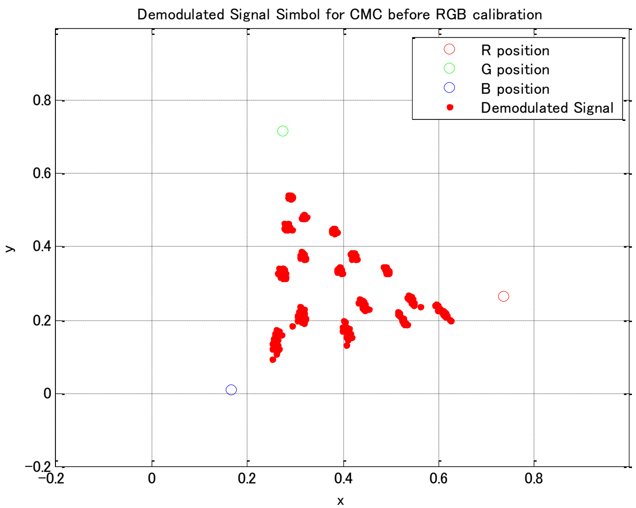
RGB Calibration



CCM system configuration with RGB calibration

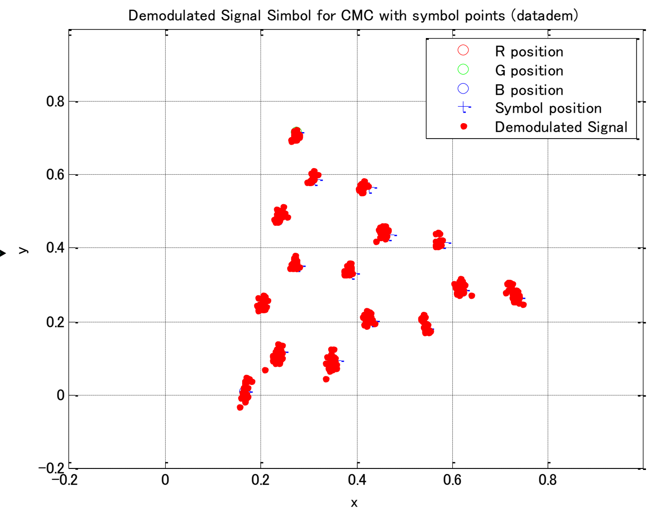
Samsung Electronics

Effect of RGB Calibration



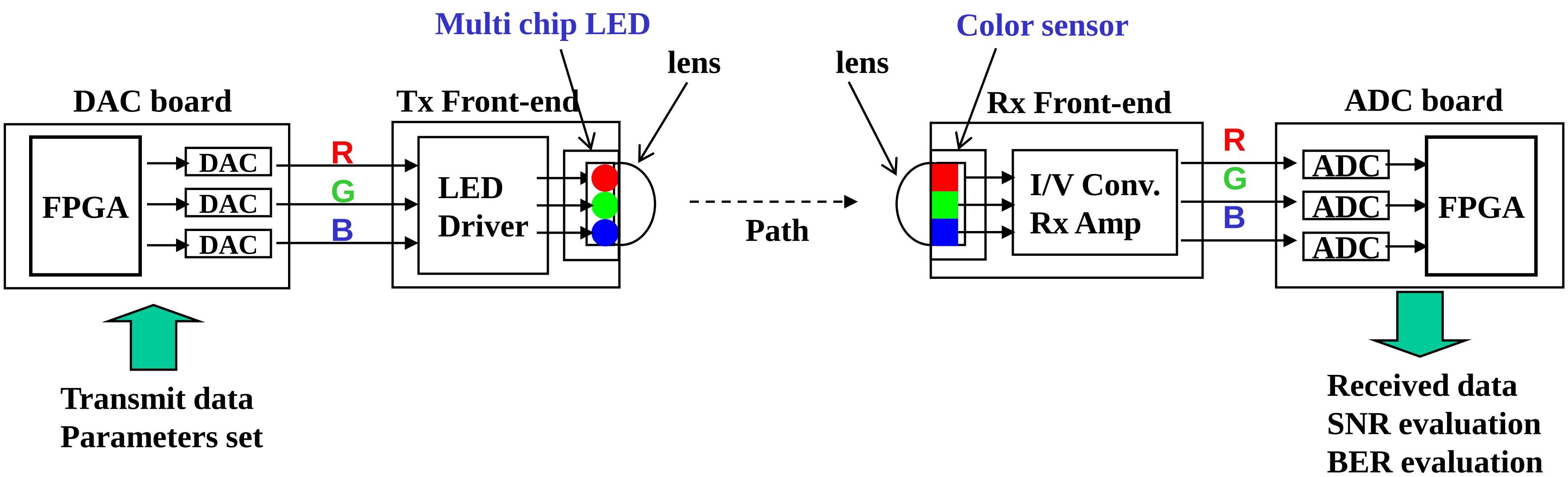
Before RGB Calibration

RGB Calibration



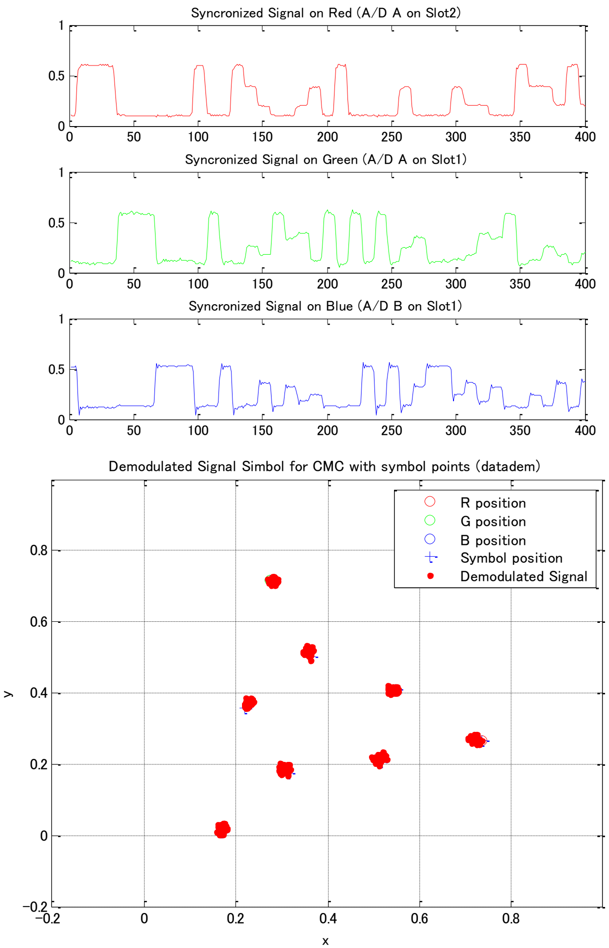
After RGB Calibration

CCM Experiment



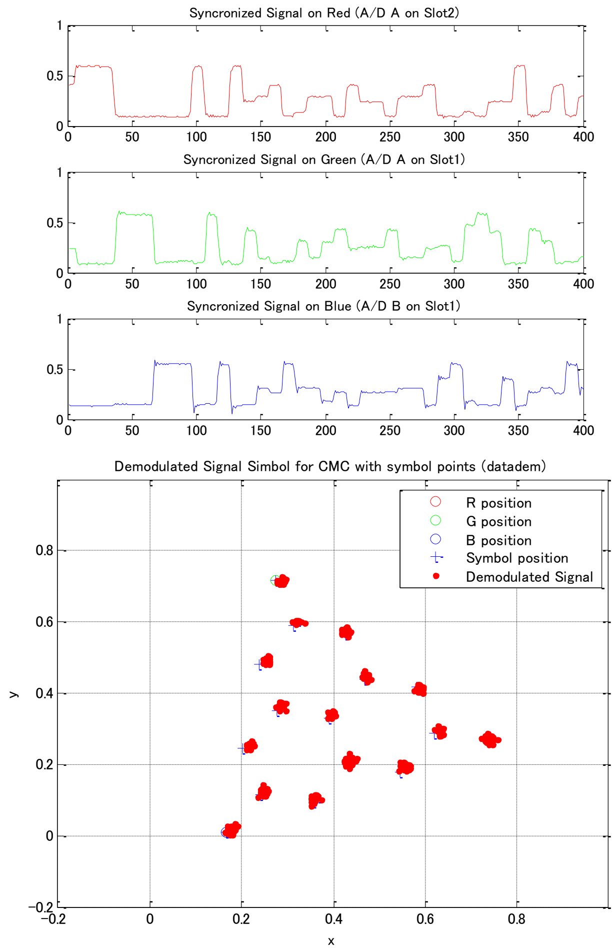
VLC Test Bed configuration

Experimental Results (10MHz/Symbol)



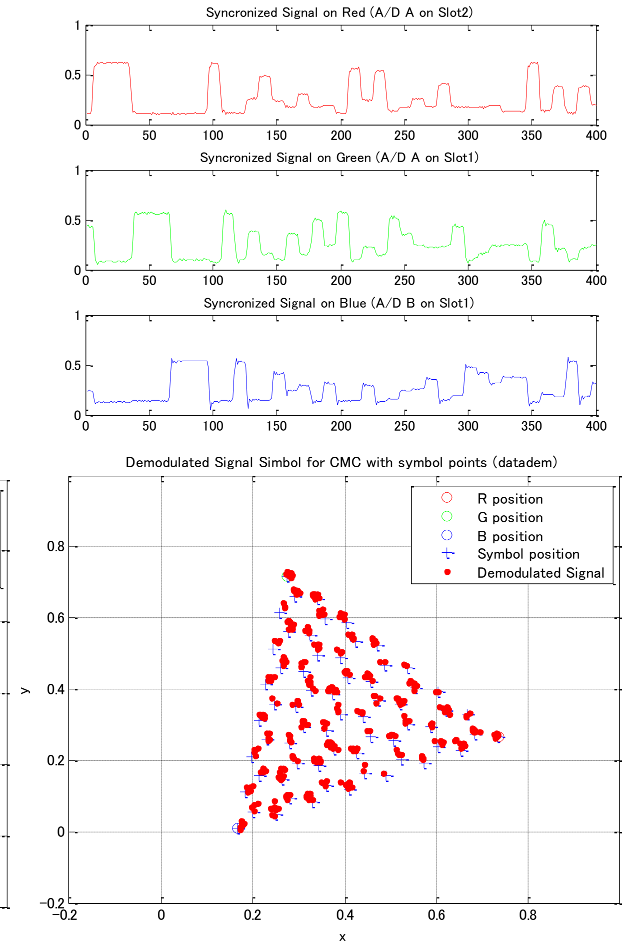
8CCM (30Mbps)

BER < 10^{-7}



16CCM (40Mbps)

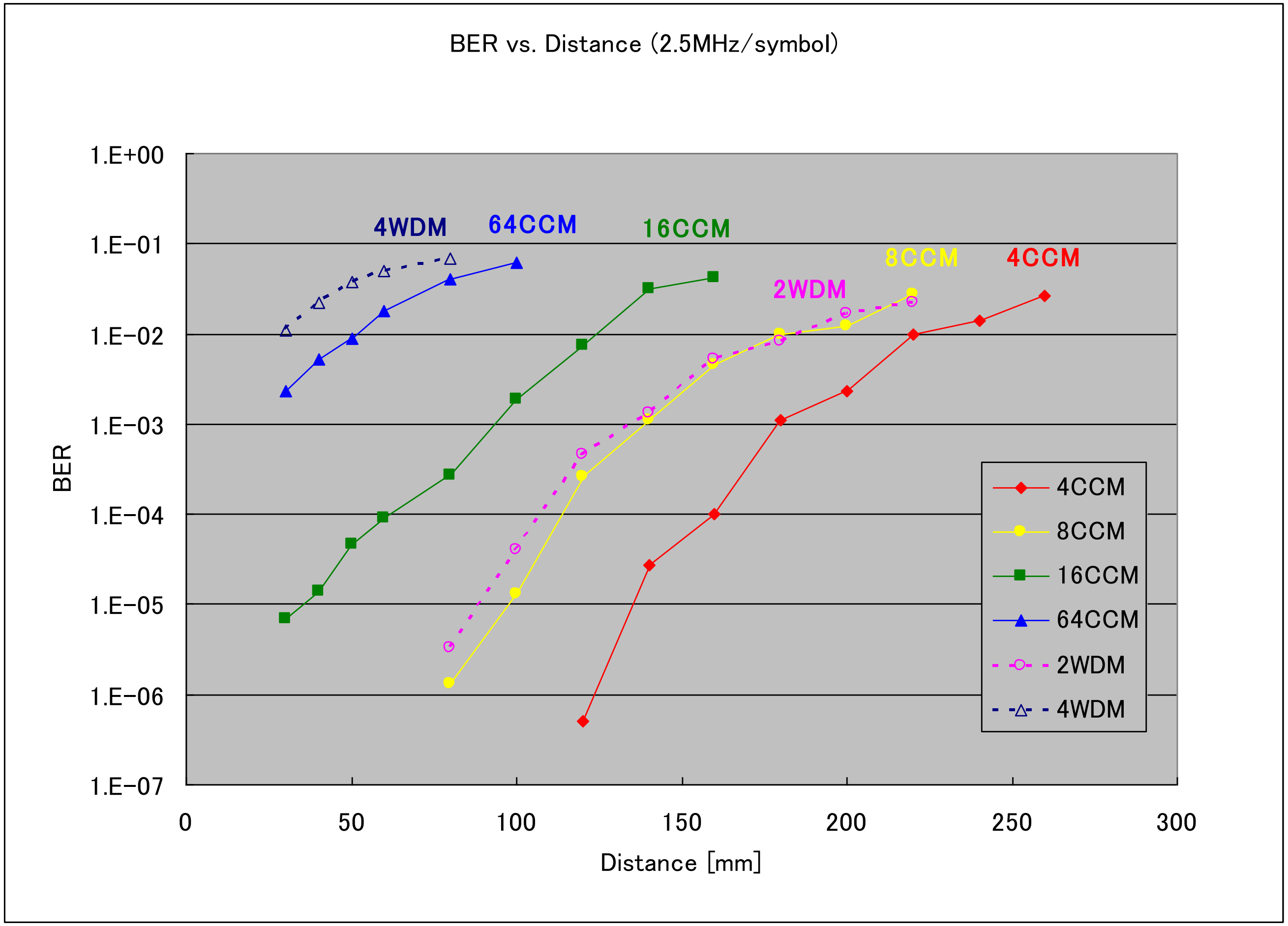
BER < 10^{-7}



64CCM (60Mbps)

BER ≒ 10^{-3}

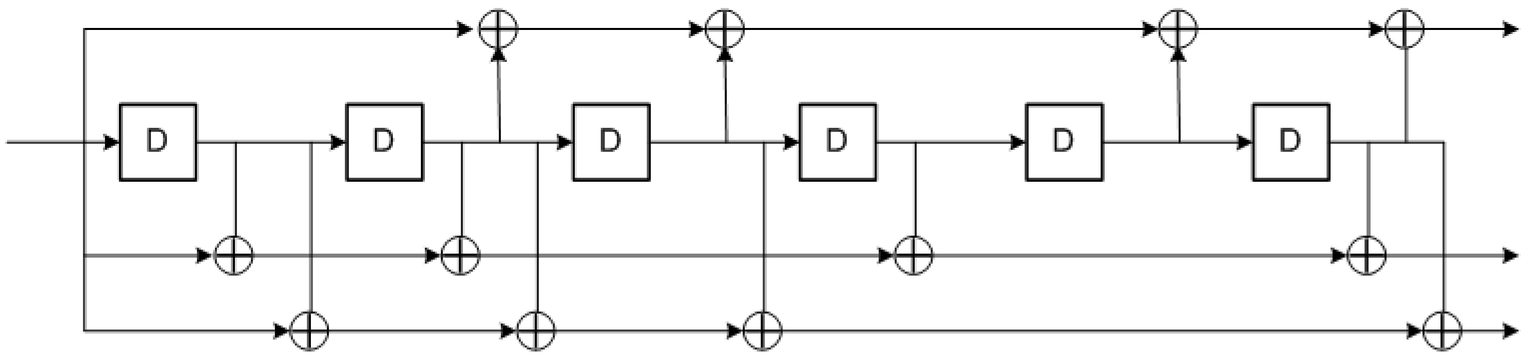
BER performance comparing with WDM



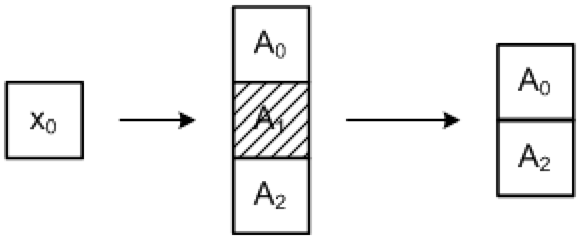
2WDM：2 levels Wave Division Multiplex (3bits/symbol) ⇔ 8CCM (3bit/symbol)
4WDM：4 levels Wave Division Multiplex (6bits/symbol) ⇔ 64CCM(6bit/symbol)

Convolutional Coding

- Encoder block
  - Constraint length : 7



  - Puncturing pattern (R = ½)



HHW BER Performance