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Source: [Atsuya Yokoi] Company [Samsung Yokohama Research Institute]
Address [2-7, Sugasawa-cho, Tsurumi-ku, Yokohama-shi, Kanagawa, 230-0027 Japan]
Voice:[+81-45-510-4240], FAX: [+81-45-510-3339], E-Mail:[atsuya.yokoi@samsung.com]

Abstract: [The introduction of the Color Multiplex Coding (CMC) for VLC and its evaluation results. The BER performances are showed by simulation and experiment.]

Purpose: [Contribution to IEEE 802.15 SG-VLC]
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Color Multiplex Coding for VLC

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Atsuya Yokoi
Samsung Yokohama Research Institute
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Introduction

- **WDM (Wave Length Multiplex)** is a good scheme for realizing high speed transmissions.
- But the wave length and number have to be selected carefully, because those decide light devices (LED, PD) and the performance of VLC systems.
- WDM system depends on the light devices strongly.

- **CMC (Color Multiplex Coding)** is a new modulation scheme which we propose.
- It doesn’t depend on the wave length and number directly.
- It can be expected better flexibility for VLC system than WDM.
What is CMC?

- 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)

\[
\begin{align*}
X &= 2.7689R + 1.7517G + 1.1302B \\
Y &= R + 4.5907G + 0.0601B \\
Z &= 0.0565G + 5.5943B \\
x &= X / (X + Y + Z) \\
y &= Y / (X + Y + Z)
\end{align*}
\]

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

- **WDM**
  - Transmit data is distributed to RGB channels.
  - The channels are decided by the wave length and number.
  - Same wave length sources and detectors are required.
  - *System flexibility is lower.*

- **CMC**
  - Transmit data is allocated in the color coordinate plane.
  - The channels are decided by the color coordinate.
  - It doesn’t depend on the wave length and number directly.
  - *System flexibility is higher.*
Why CMC?

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

Symbol position in xy color coordinate for CMC performance evaluation

- Those symbol positions were decided for having same distance from adjacent symbols.

4 CMC: 4 points Color Multiplex Coding (2 bits/symbol)
16 CMC: 16 points Color Multiplex Coding (4 bits/symbol)
64 CMC: 64 points Color Multiplex Coding (6 bits/symbol)
BER performance with random noise

- 64CMC and 4WDM have same ability for transmitting speed ratio (6bits/symbol).
- CMC has 3dB lower BER performance in the random noise environment.
BER performance with common mode noise

Random Noise & Common mode Noise vs. BER

- **64CMC_r3**: 64points CMC (6bits/symbol) with Random Noise & +3dB Common mode Noise
- **4WDM_r3**: 4level/color WDM (6bits/symbol) with Random Noise & +3dB Common mode Noise

- 64CMC and 4WDM have same ability for transmitting speed ration.
- CMC has 1.5dB higher BER performance in the common mode noise environment.
CMC Experiment

VLC Test Bed

PC

Software

Hardware

Driver

CMC Algorithm

Digital board

Transmitter

FPGA

DAC

DAC

DAC

Receiver

FPGA

ADC

ADC

ADC

VLC-Tx

Front-end

LED: UVGB1306L

Light Prop.

VLC-Rx

Front-end

PD: S9702

USB

I/F

USB 2.0

HDD

DAC

DAC

DAC

ADC

ADC

ADC

R ch1

G ch2

B ch3

R ch1

G ch2

B ch3

USB

I/F

USB

I/F

USB

I/F

USB

I/F
Experimental Results (2.5MHz/Symbol)

4CMC (5Mbps)  
BER < 10^-6

16CMC (10Mbps)  
BER < 10^-6

64CMC (15Mbps)  
BER ≒ 10^-4
Experimental Results (5MHz/Symbol)

Demodulated Signal Symbol for CMC with symbol points (datadem)

4CMC (10Mbps)  BER < 10^{-6}

16CMC (20Mbps)  BER < 10^{-6}

64CMC (30Mbps)  BER ≅ 10^{-3}
Experimental Results (10MHz/Symbol)

4CMC (20Mbps)  
BER < 10^{-6}

16CMC (40Mbps)  
BER ≈ 10^{-2}

64CMC (60Mbps)  
BER > 10^{-1}
Experimental Results

BER performance

Bit Rate [Mbps]

BER

4CMC: 4 points Color Multiplex Coding (2 bits/symbol)
16CMC: 16 points Color Multiplex Coding (4 bits/symbol)
64CMC: 64 points Color Multiplex Coding (6 bits/symbol)
Conclusion

- We proposed CMC as a new modulation scheme.
- CMC can provide more flexible VLC system than WDM.
- CMC has better performance than WDM in some case.
- We confirmed 20Mbps transmission on 16CMC.
- We can expect higher transmission speed by using the device (LED, PD) which has wider frequency band.
Thank you for your attention!