**IEEE P802.15**

**Wireless Personal Area Networks**

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| Project | IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs) |
| Title | **Kookmin PHY 4 modes –**<br>**hybrid modulation schemes and cameras ISC modes** |
| Date Submitted | [March, 2016] |
| Source | Yeong Min Jang, Trang Nguyen (Kookmin University) |
| Re: | |
| Abstract | This document gives text detail of a modulation scheme (S2-PSK) that is operating for both global shutter camera and rolling shutter camera as a receiver.<br>Also, the document describes a twinkle modulation scheme, a hybrid scheme of S2-PSK and DS8-PSK that is for dual-camera system. A S2-PSK signal is for both types of shutter camera receivers, and a DS8-PSK signal is for high speed data transmission to a global shutter camera receiver. |
| Purpose | Text input to draft D0. |
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# Table of Content

# 1.0 PHY 4 Layer Operating mode(s)

Optical Camera Communications is introducing three new operating modes.

- **PHY 4 accommodates Rolling/Global Shutter Cameras and Low Rate PD**
- PHY 5 accommodates Rolling Shutter Cameras
- PHY 6 accommodates 2 Dimensional Screen Codes

| PHY 4 Operating Modes | | | | |
|---|---|---|---|---|
| **Modulation** | **Tx [1] Symbol rate** | **Rx Frame rate** | **FEC** | **Data Rate[5]** |
| S2-PSK | 5/10/15 | Rx(fps) >Tx [2] | Outer FEC code[3] | Uncoded data rate is equal to the symbol rate |
| S8-PSK | | | Outer FEC code[3] bad-sampling decoding[4] | Uncoded data rate is triple the symbol rate |
| DS8-PSK | | | Outer FEC code[3] bad-sampling decoding[4] | Uncoded data rate is triple the symbol rate |
| | | | | |

[1] Optical Clock Rate: A constant frequency is chosen to modulate data. The optical clock rate does not affect to the data rate, only symbol rate is concerned to data rate. Any frequency can be used for optical clock rate; however, notice that it must be no less than 200Hz (eye cut-off) and upper-limited due to the limited capacity of a global shutter speed of a camera receiver.

[2] Oversampling condition: The sampling rate of camera (fps) must be no less than the symbol rate of transmission.

[3] Outer FEC code: When the shutter speed of a global shutter camera is considerable short (compared to the optical clock rate of LED), the error caused by long exposure time is corrected by an outer code.

[4] Bad-sampling decoding: A bad-sampled image is an image that captured on a switching time of LEDs states (x_state is an unclear state of a LED), caused by long exposing time. An algorithm for decoding under presence of bad-sampling was proposed in slide 22 (Kookmin sub-proposal, number 802.15-16-0015-02-007a). The algorithm does not cost any data rate consumption (none reducing data for line/space coding).

[5] Data rate calculation: Data rate on a spatial modulation scheme depends on the number of LEDs. To operate, S2-PSK needs a couple of LEDs (one LED is a reference, another (or the other LEDs) is for data); S8-PSK needs a group of four LEDs to transmit three bits; DS8-PSK needs a group of eight LEDs to transmit three bits.

| | **S2-PSK** | **S8-PSK** | **DS8-PSK** |
|---|---|---|---|
| **Data rate [bps]** | $R_{bit}$ = (bit/symbol) x (symbol rate) = (K) x 10 | $R_{bit}$ = (bit/symbol) x (symbol rate) = (3×K/4) x 10 | $R_{bit}$ = (bit/symbol) x (symbol rate) = (3×K/8) x 10 |
| **Advantages** | - Highest data rate | - Support for decoding even under presence of bad-sampling due to long-exposure time | - Dimming supported in steps of 12.5% |

where K is the number of data LEDs on a transmitter

# 2.0 PHY 4 specifications

## Definition

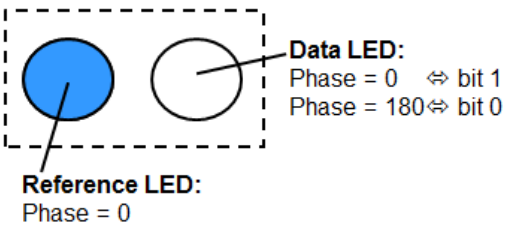
- **spatial phase** (**S_Phase**)**:** the phase of a discrete waveform which is built from the states of LEDs on a group those captured and decoded from a global shutter image.
- **global phase shift:** the phase value that all LEDs in a *data group* together are shifted to transmit data.
- **data group:** A group of data LEDs those operate together to transmit a data symbol
- **reference group:** A group of reference LEDs those operate together to transmit a reference signal
- **S_Phase shift:** the abstraction value between the *spatial phase* values of *data group* and of the *reference group*.
- **(long exposure) bad-sampled image:** an image sampling that captures an unclear sate of LED (neither ON nor OFF) due to long exposure time.
- **x_state** (of a LED): an unclear state that observed from a bad-sampled image.
- **SM-PSK** (e.g. **S2-PSK; S8-PSK**; etc.)**:** Spatial Multiple-Phase Shift Keying
- **DSM-PSK** (e.g**. DS8-PSK**): Dimmable SM-PSK

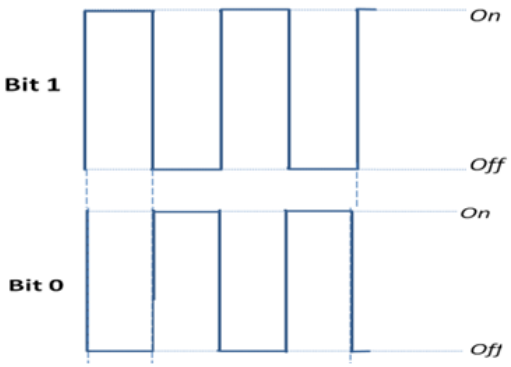
## 2.1 Spatial 2-PSK (S2-PSK)

### 2.1.1 S2-PSK Encoder

- **Bit definition (Encoding):**
  - Same frequency and amplitude
  - Inverse phase

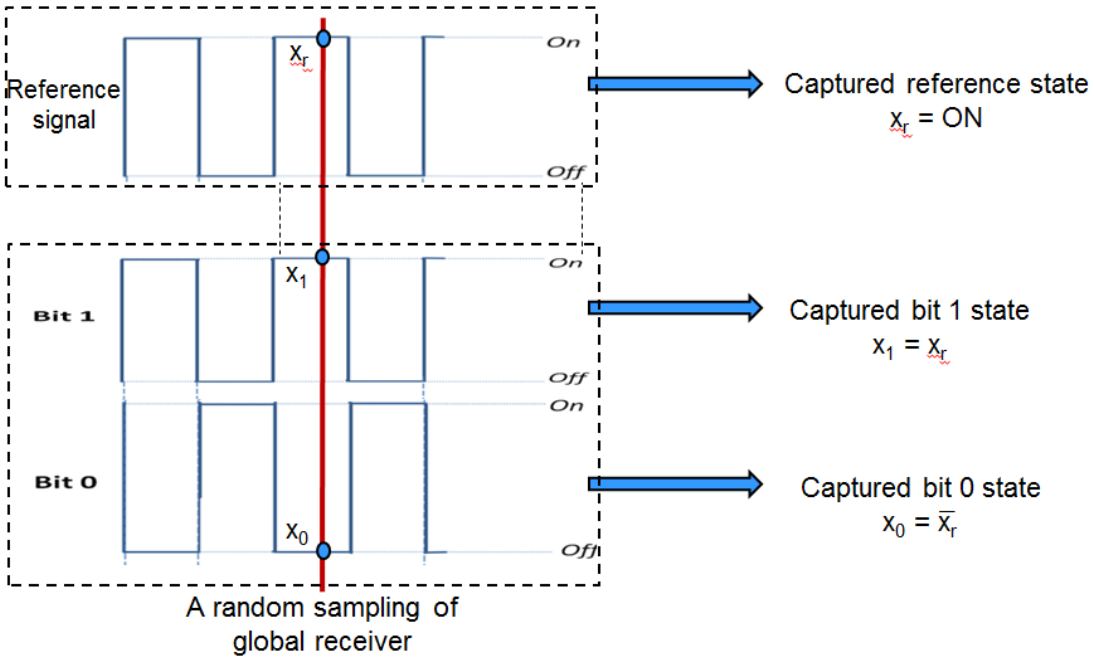
  (bit 1 phase = 0; bit 0 phase = 180



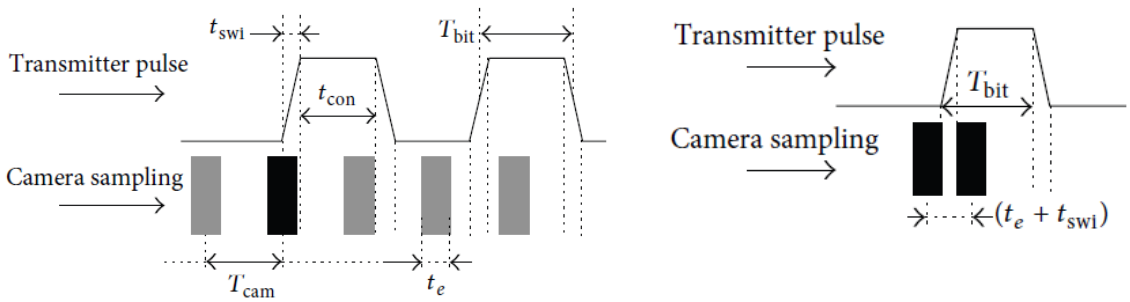

- **Decoding principle (applied for a random sampling):**
  - The state of bit 1 is always equal to the state of the reference signal **($x_1 = x_r$)**
  - The state of bit 0 is always inverse to the state of the reference signal **($x_0 = \overline{xr}$)**

**Decoding example**:




- **Compatibility support**
  - The decoding result is non-affected by the state of the LEDs but by the comparison. This means a receiver does not need to know which LED is a reference LED and which one is data LED; data is output from a comparison.
  - The principle is compatible to different frame rate variation.

### 2.1.2 S2-PSK Error Correction




- **Modulation considered**
  - Modulation frequency is less than the global shutter speed of the camera (e.g. 1 kHz)
  - The long exposure causes error (BER)

Error is caused by long exposing time in a global shutter camera receiver

An outer FEC code is required to correct the error.

### 2.1.3 S2-PSK Dimming Support

No dimming support is considered in this scheme. The brightness is constant at 50%.

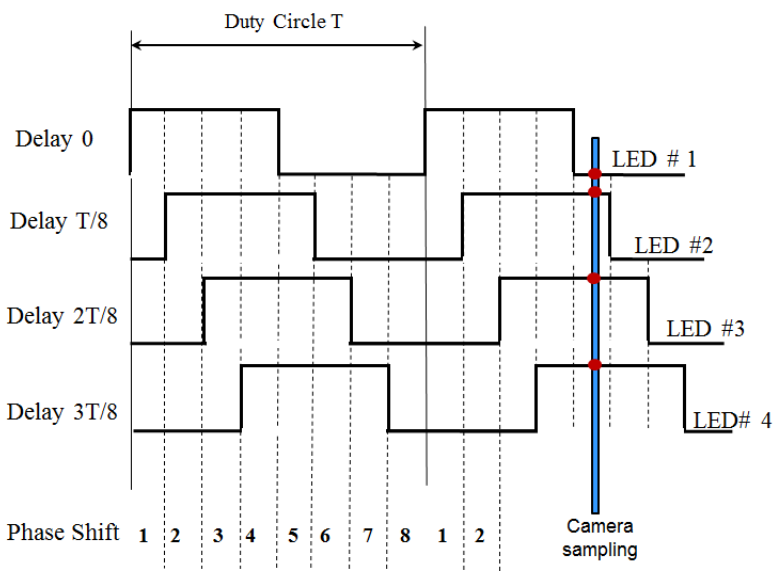
Amplitude Modulation can be used in order to dim the light if necessary. This is reasonable because the optical clock rate to modulate all LEDs is constant throughout transmitting time.

## 2.2 Spatial 8-PSK (S8-PSK)

### 2.2.1 S8-PSK Encoder

A group of four-LEDs is used to transmit a phase which encoded by 3-bits data.

**A Spatial Phase** (of a LEDs group): is defined by a four-sates set of a LEDs group.




**Spatial-Phase Definition Table**

| A discrete waveform (4-States) **Input** | Spatial Phase (S_Phase) **Output** |
|---|---|
| 1000 | 1 |
| 1100 | 2 |
| 1110 | 3 |
| 1111 | 4 |
| 0111 | 5 |
| 0011 | 6 |
| 0001 | 7 |
| 0000 | 8 |

## Encoding:

A Global Phase Shift of a group of data LEDs determines how LEDs are modulated. It is generated according to 3bits data input.

**Decoding table - case 1 (none bad-sampling)**

**Encoding Table**

| 3-bits Input | Global Phase Shift Output |
|---|---|
| 000 | 0 |
| 001 | 1 |
| 010 | 2 |
| 011 | 3 |
| 100 | 4 |
| 101 | 5 |
| 110 | 6 |
| 111 | 7 |

**Decoding Tables**

**States-to-Phase Table**

| A discrete waveform (4-States) Input | Spatial Phase (S_Phase) Output |
|---|---|
| 1000 | 1 |
| 1100 | 2 |
| 1110 | 3 |
| 1111 | 4 |
| 0111 | 5 |
| 0011 | 6 |
| 0001 | 7 |
| 0000 | 8 |

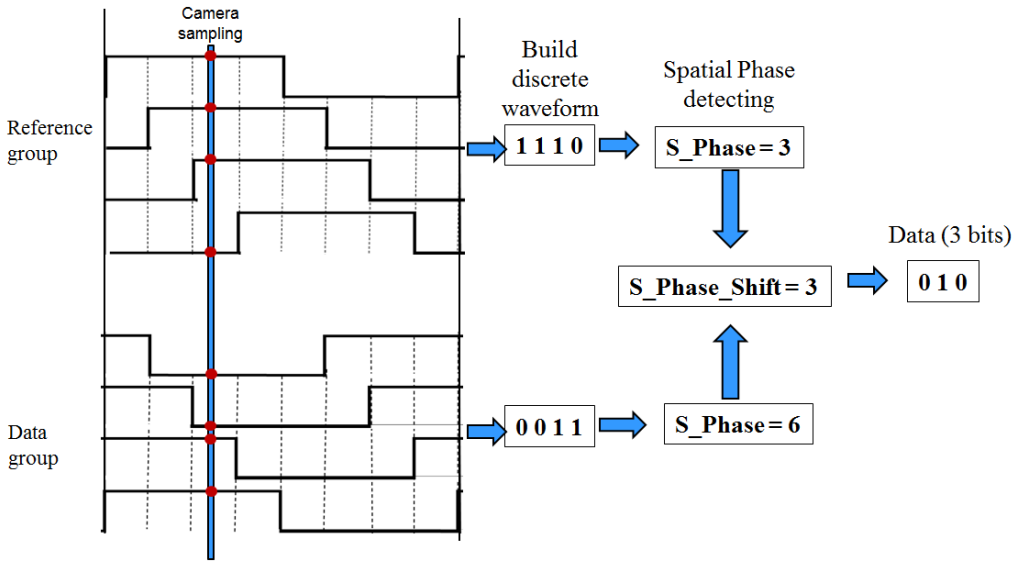
**Phase-to-Bits Table**

| (S_Phase_Shift) Input | 3-bits Output |
|---|---|
| 0 | 000 |
| 1 | 001 |
| 2 | 010 |
| 3 | 011 |
| 4 | 100 |
| 5 | 101 |
| 6 | 110 |
| 7 | 111 |

## Decoding:

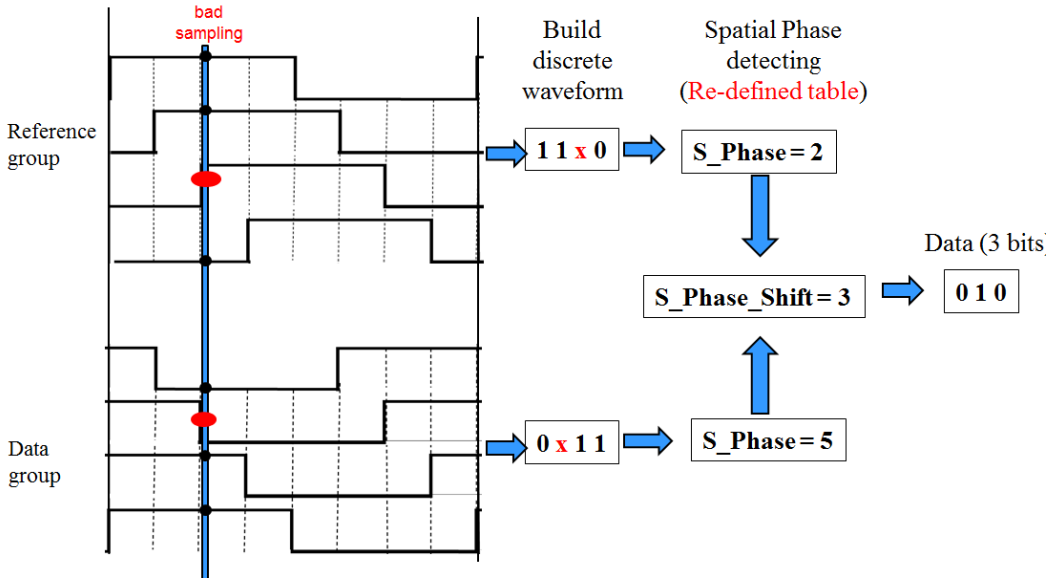
S_Phase Shift = S_Phase(data) – S_Phase(reference)

**Case 1:** Decoding under none-presence of bad-sampling




Decoding tables (none bad-sampling) are used

**Case 2**: Decoding under presence of *bad-sampling*




Decoding tables (presence of bad-sampling) are used

### 2.2.2 S8-PSK Error Correction

Error caused by bad-sampling (long exposure time): is corrected by a redefined decoding tables

**Re-defined Decoding table - case 2 (presence of bad-sampling)**

**States-to-Phase Table (2)**

| A discrete waveform (4-States) Input | Spatial Phase (S_Phase) Output |
|---|---|
| 1x00 | 1 |
| 11x0 | 2 |
| 111x | 3 |
| x111 | 4 |
| 0x11 | 5 |
| 00x1 | 6 |
| 000x | 7 |
| x000 | 8 |

**Phase-to-Bits Table**

| (S_Phase_Shift) Input | 3-bits Output |
|---|---|
| 0 | 000 |
| 1 | 001 |
| 2 | 010 |
| 3 | 011 |
| 4 | 100 |
| 5 | 101 |
| 6 | 110 |
| 7 | 111 |

The correction of bad-sampling error does not require any line/space coding; hence no reduce to data rate.

Additionally, an outer FEC code can be used. See IEEE 802.15.7 standard for generating outer code.

### 2.2.3 S8-PSK Dimming Support

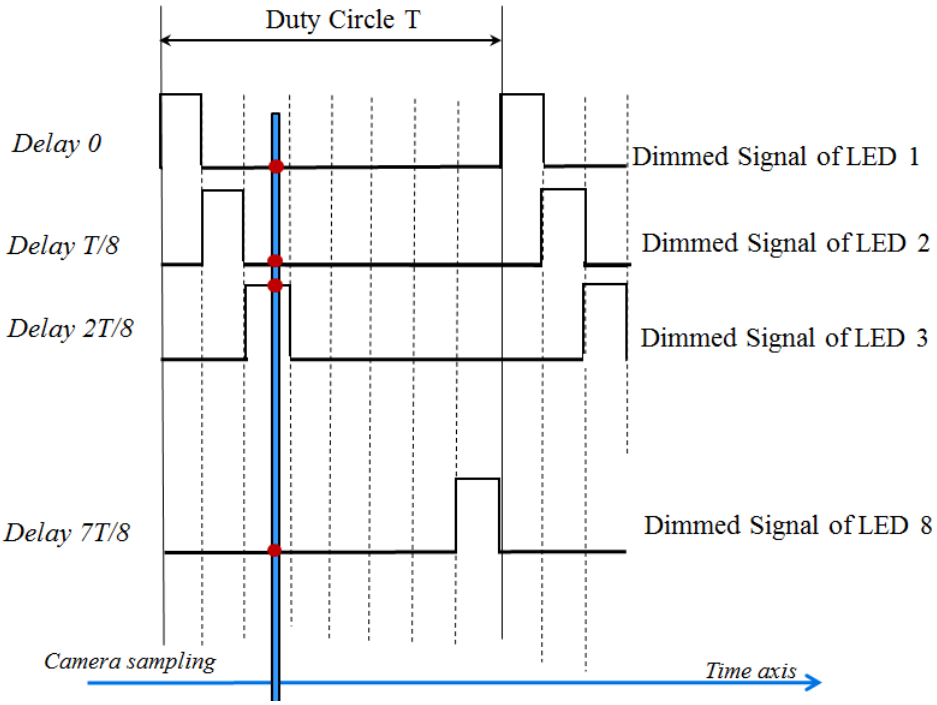
No dimming support is considered in this scheme. The brightness is constant at 50%.

Amplitude Modulation can be used in order to dim the light if necessary. This is reasonable because the optical clock rate to modulate all LEDs is constant throughout transmitting time.

## 2.3 Dimmable Spatial 8-PSK (DS8-PSK)

### 2.3.1 DS8-PSK Encoder

- **Principles**
  - 8 LEDs per group together define a spatial-phase (with dimming supported)




- **Encoding**
  - A reference group: *Global Phase Shift* = 0
  - A data group: *Global Phase Shift* = 0/1/…/7

**Encoding Table**

| 3-bits Input | Global Phase Shift Output |
|---|---|
| 000 | 0 |
| 001 | 1 |
| 010 | 2 |
| 011 | 3 |
| 100 | 4 |
| 101 | 5 |
| 110 | 6 |
| 111 | 7 |

**Decoding Tables (Phase-to-Bits Table)**

| S_Phase_Shift Input | 3-bits Output |
|---|---|
| 0 | 000 |
| 1 | 001 |
| 2 | 010 |
| 3 | 011 |
| 4 | 100 |
| 5 | 101 |
| 6 | 110 |
| 7 | 111 |

**S_Phase Decoding table for DS8-PSK**

1/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1000 0000 | 1 |
| 0100 0000 | 2 |
| 0010 0000 | 3 |
| 0001 0000 | 4 |
| 0000 1000 | 5 |
| 0000 0100 | 6 |
| 0000 0010 | 7 |
| 0000 0001 | 8 |

2/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1000 0001 | 1 |
| 1100 0000 | 2 |
| 0110 0000 | 3 |
| 0011 0000 | 4 |
| 0001 1000 | 5 |
| 0000 1100 | 6 |
| 0000 0110 | 7 |
| 0000 0011 | 8 |

3/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1000 0011 | 1 |
| 1100 0001 | 2 |
| 1110 0000 | 3 |
| 0111 0000 | 4 |
| 0011 1000 | 5 |
| 0001 1100 | 6 |
| 0000 1110 | 7 |
| 0000 0111 | 8 |

4/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1000 0111 | 1 |
| 1100 0011 | 2 |
| 1110 0001 | 3 |
| 1111 0000 | 4 |
| 0111 1000 | 5 |
| 0011 1100 | 6 |
| 0001 1110 | 7 |
| 0000 1111 | 8 |

5/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1000 1111 | 1 |
| 1100 0111 | 2 |
| 1110 0011 | 3 |
| 1111 0001 | 4 |
| 1111 1000 | 5 |
| 0111 1100 | 6 |
| 0011 1110 | 7 |
| 0001 1111 | 8 |

6/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1001 1111 | 1 |
| 1100 1111 | 2 |
| 1110 0111 | 3 |
| 1111 0011 | 4 |
| 1111 1001 | 5 |
| 1111 1100 | 6 |
| 0111 1110 | 7 |
| 0011 1111 | 8 |

7/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1011 1111 | 1 |
| 1101 1111 | 2 |
| 1110 1111 | 3 |
| 1111 0111 | 4 |
| 1111 1011 | 5 |
| 1111 1101 | 6 |
| 1111 1110 | 7 |
| 0111 1111 | 8 |

### 2.3.2 DS8-PSK Error Correction

Error caused by bad-sampling (long exposure time): is corrected by a redefined decoding tables (below). No reduce to data rate.

In addition, an outer FEC code is used. See IEEE 802.15.7 standard for generating outer code.

**S_Phase Decoding Re-defined tables for DS8-PSK** (presence of x_state in bad-sampling)

1/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| xx00 0000 | 1 |
| 0xx0 0000 | 2 |
| 00xx 0000 | 3 |
| 000x x000 | 4 |
| 0000 xx00 | 5 |
| 0000 0xx0 | 6 |
| 0000 00xx | 7 |
| x000 000x | 8 |

2/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1x00 000x | 1 |
| x1x0 0000 | 2 |
| 0x1x 0000 | 3 |
| 00x1 x000 | 4 |
| 000x 1x00 | 5 |
| 0000 x1x0 | 6 |
| 0000 0x1x | 7 |
| x000 00x1 | 8 |

3/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1x00 00x1 | 1 |
| 11x0 000x | 2 |
| x11x 0000 | 3 |
| 0x11 x000 | 4 |
| 00x1 1x00 | 5 |
| 000x 11x0 | 6 |
| 0000 x11x | 7 |
| x000 0x11 | 8 |

4/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1x00 0x11 | 1 |
| 11x0 00x1 | 2 |
| 111x 000x | 3 |
| x111 x000 | 4 |
| 0x11 1x00 | 5 |
| 00x1 11x0 | 6 |
| 000x 111x | 7 |
| x000 x111 | 8 |

5/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1x00 x111 | 1 |
| 11x0 0x11 | 2 |
| 111x 00x1 | 3 |
| 1111 x00x | 4 |
| x111 1x00 | 5 |
| 0x11 11x0 | 6 |
| 00x1 111x | 7 |
| x00x 1111 | 8 |

6/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1x0x 1111 | 1 |
| 11x0 x111 | 2 |
| 111x 0x11 | 3 |
| 1111 x0x1 | 4 |
| 1111 1x0x | 5 |
| x111 11x0 | 6 |
| 0x11 111x | 7 |
| x0x1 1111 | 8 |

7/8 Dimming

| 8-States Input | S_Phase Output |
|---|---|
| 1xx1 1111 | 1 |
| 11xx 1111 | 2 |
| 111x x111 | 3 |
| 1111 xx11 | 4 |
| 1111 1xx1 | 5 |
| 1111 11xx | 6 |
| x111 111x | 7 |
| xx11 1111 | 8 |

where x state (of a LED) is an unclear state that observed from a bad-sampled image.

### 2.3.3 DS8-PSK Dimming Support

- ❑ Dimming is supported in steps of 1/8 (12.5%) in DS8-PSK scheme
- ❑ The encoding table (to determine the global shift value of a data LEDs group) is common for all dimming level. Each dimming level is supported by a specific S_Phase decoding table (or a re-defined table) that is different from the other dimming levels.

**Decoding procedure under dimming condition:**

**Step 1***:* Choose the proper **S_Phase decoding Table** (among 7 tables) according to the dimming level:

- **Dimming level** $= \frac{\sum "\mathbf{1}"}{\mathbf{8}}$ (or $= \frac{1+\sum "1"}{8}$ under presence of x_state)
- Select the proper **S_Phase decoding table**

**Step 2:** Map with the selected decoding table to find **S_Phase(data)**; **S_Phase(reference)** and **S_Phase_Shift**

**Input:** The discrete waveforms of a 8-LEDs groups (a reference group and data groups)

**Output:** Spatial Phases

- S_Phase(reference)
- S_Phase(data)
- S_Phase_Shift = S_Phase(data) - S_Phase(reference)

**Step 3**: Data decoding using Phase-to-Bits table

**Input:** S_Phase_Shift

**Output:** 3 data bits

## 2.4 Twinkle VPPM

### 2.4.1 Twinkle S2-PSK and DS8-PSK Encoder

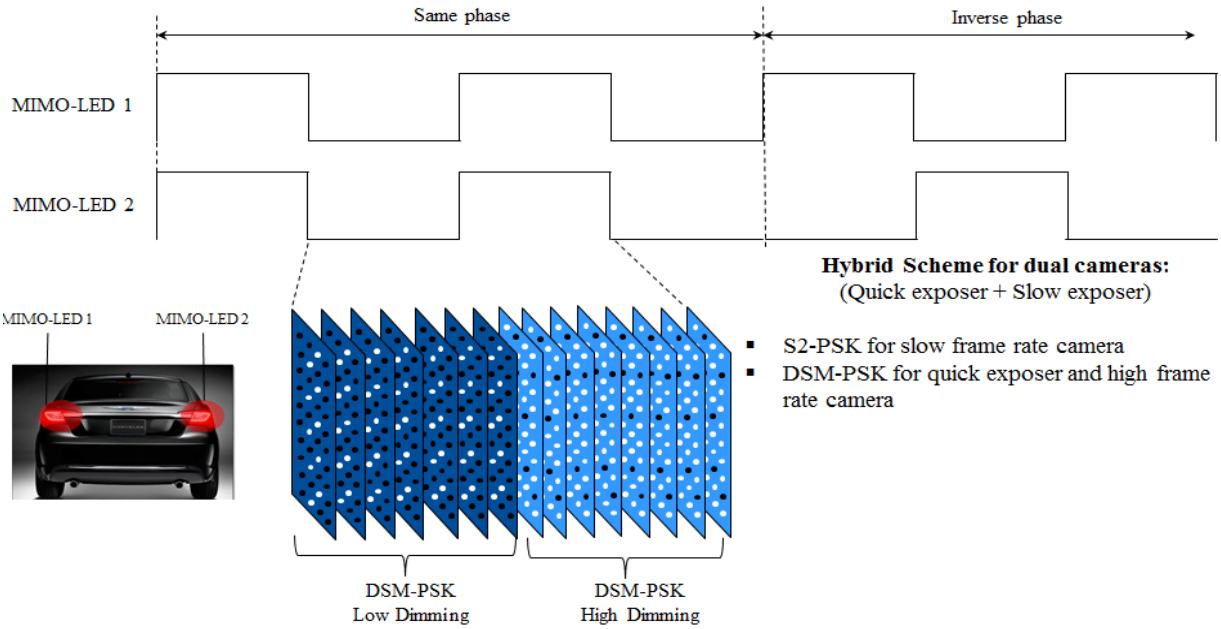
The idea of a twinkle signal came from Intel. It was to support dual-cameras system. This section presents a same purpose in using dual-cameras; however by using Kookmin modulation schemes: a hybrid scheme of S2-PSK and DSM-PSK.

- Twinkle VPPM? Even though our modulation names are different (Spatial PSK), a modulated signal to a single LED is also a VPPM signal. So the technique title "Twinkle VPPM" is fine to us. We respect and follow the title name.

A twinkle signal (hybrid modulation scheme of S2-PSK and DS8-PSK) for a dual-camera system:
- A low frame rate camera (i.e. low cost camera) detects S2-PSK signal

- Can be either a global or a rolling shutter camera
- Can be either a slow exposer or a quick exposer camera. A higher shutter speed camera is better for removing environmental noise and detecting LEDs.

- A high speed camera (i.e. a global shutter and high frame rate camera) decode data at DS8-PSK signal.





| MIMO LED 1 | MIMO LED 2 |
|---|---|

### 2.3.2 Twinkle S2-PSK and DS8-PSK Error Correction

Error caused by bad-sampling (long exposure time): is corrected by a re-defined decoding tables in DS8-PSK scheme.

In addition, an outer FEC code can be applied, or just a repeat code for simple.

### 2.3.3 Twinkle S2-PSK and DS8-PSK Dimming Support

Dimming is supported by adjusting the low dimmed level and high dimmed level of DS8-PSK scheme to output a desired dimming level.

Output dimming level = ½ (low dimmed level + high dimmed level)