IEEE P802.15

Wireless Personal Area Networks

Project	IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)
Title	**Kookmin PHY 5 modes: (Flicker-free) Rolling Shutter Modes for ISC**
Date Submitted	[March, 2016]
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Re:	
Abstract	This document gives text detail of two modulation schemes for rolling shutter ISC, including a Compatible-OOK (C-OOK) modulation scheme (oversampling mode and error detection mode) and a compatible M-FSK (CM-FSK).
Purpose	Text input to draft D0.
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1. PHY 5 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

Table. Flicker-free Rolling Shutter PHY 5 Operating Modes

Modulation	RLL Code	Tx optical Clock Rate	Rx frame rate	Frame Length	FEC	OH	PHY SAP throughput (bps)
C-OOK	Manchester	Clock rate = 2.2 kHz Symbol rate = **10**	Rx(fps) >Tx [1]	DS=**100**[2]	None	Preamble +Ab	60
	4B6B			DS=**60**[4]	None		150
	Manchester	Clock rate = 4.4 kHz Symbol rate = **20**	Rx(fps) ~ Tx[3]	DS=**60**[4]	Outer code[5]	Preamble +2.Ab	580
	4B6B			DS=**60**[4]			700
Modulation	**Coding**	**Tx (freq.# /symbol rate)**	**Rx frame rate**	**FEC**		**OH**	**PHY SAP throughput (bps)**
CM-FSK	None	#_of_Freq. = 32 Symbol rate = 10	Rx(fps) ≥ 2.Tx	None		Ab (per symbol)	40
	2-PSK						50
	4-PSK	#_of_Freq. = 64 Symbol rate = 10		Outer FEC code[6]			70

[1] Oversampling Mode (repeat code): The frame rate is assumed above the symbol rate all the time. Additionally, a majority voting is applied to improve BER.

[2] Short frame mode: The data frame length is short at 10 ms. At short frame mode, transmission can be supported at long distance where the size of LED seen on an image is considerable small.

[3] Error Detection Mode: The error which is caused by frame rate drop (to below the symbol rate) can be detected by using two asynchronous bits. Consequently, a high symbol rate of transmission can be performed.

[4] Long frame mode: The data frame length is longer at 16.67 ms to transmit more data per packet. In addition, a data fusion technique (fusing data parts on two adjacent images into a complete packet) helps a receiver in recovering an entire packet under asynchronous condition.

[5, 6] Outer FEC code: To correct the error which caused by frame rate drop (to below the symbol rate) when being detected.

2. PHY 5 specifications

2.1 Prototypes

2.1.1 Compatible OOK Modulation Scheme

Compatibility supports to various image sensors:

- Frame rates variation
- Different sampling rates
- Different rolling exposure times

Definition

- **varying frame rate ISC mode:** an ISC mode that supports a varying frame-rate receiver.
- **asynchronous decoding:** a decoding procedure under presence of frame rate variation.
- **optical clock rate** (**modulation rate**): The frequency at which the data is clocked out to the optical source. In flicker-free mode, let assume the frequency no less than 200Hz to be invisible to human eyes.
- **asynchronous bit:** a form of *clock information* in the temporal scheme helping a varying frame rate receiver in asynchronous-decoding. Note that this is not only necessarily one single bit (bit 1 or bit 0), but also can be a symbol (a set of bits in which symbol 1 and symbol 0 are orthogonal somehow) to operate at high noise affected.
- **clock information (of a data packet/symbol)**: The information represents the state of a symbol clocked out. The clock information is transmitted along with a symbol to help a receiver identifying an arrival state of new symbol under presence of frame rate variation.
- **rolling exposure time:** the time from the first line to the last line exposes to light in a rolling shutter image sensor.
- **rolling sampling rate:** how may row of pixels exposed to light in a rolling shutter camera
-
- **forward decoding:** a decoding process in asynchronous decoding that taken from the position of the SF (preamble of the OOK data frame structure) backward on a rolling image.
- **backward decoding:** a decoding process in asynchronous decoding that taken from the position of the SF (preamble of the OOK data frame structure) forward on a rolling image.
- **packet recovery:** a process in asynchronous decoding that recovers a complete data packet from the incomplete data parts decoded, forward and backward part of one (two) data packet(s).
- **data fusion:** a process in asynchronous decoding to group data parts (forward and backward parts) those belong to one packet. There are two types of data fusion that happens according to the value of asynchronous bits:
  - inter-frame fusion: to group data parts from different images (usually two images, but can be more than two)
  - intra-frame fusion: to group data parts from an image.
- **DS rate:** the frequency at which the data subframe is clocked out to the transmission medium.

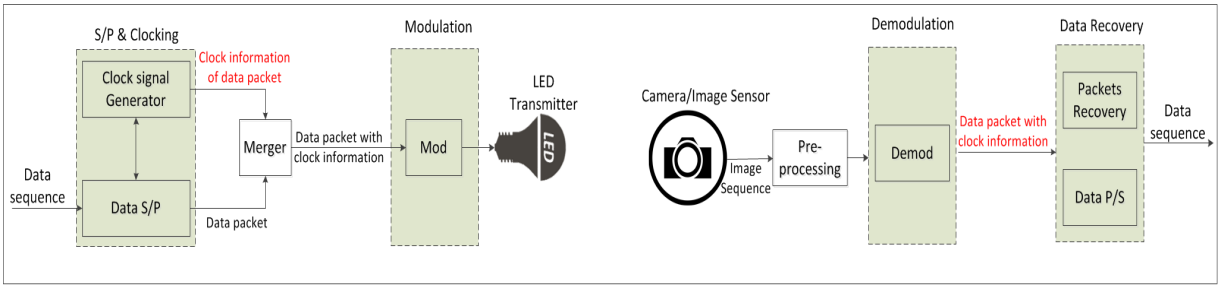


Figure1. System Architecture for clock transmission approach in time domain

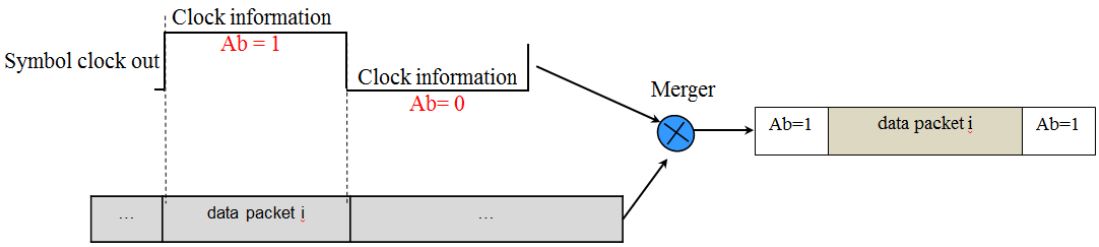


Figure 2: Data and clock information merging in time domain

- ***clock information (of a data packet)****:* In this scheme, asynchronous bits (Ab) are in form of clock information.

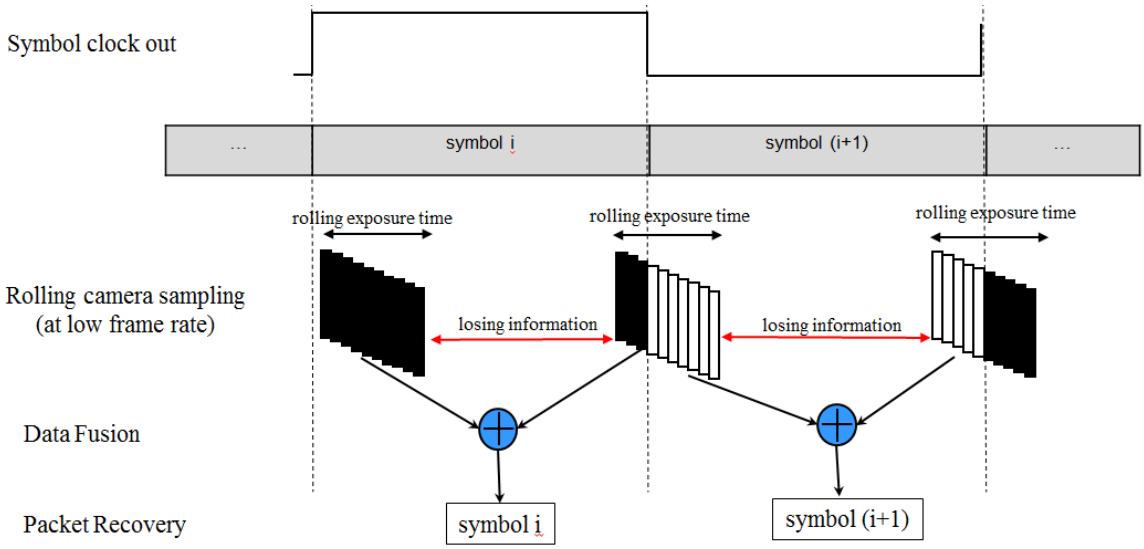


Figure 3: Packet Recovery

2.1.2 Compatible M-FSK Modulation Scheme

Compatibility supports:

- Frame rate variation
- Different sampling rates and shutter speeds

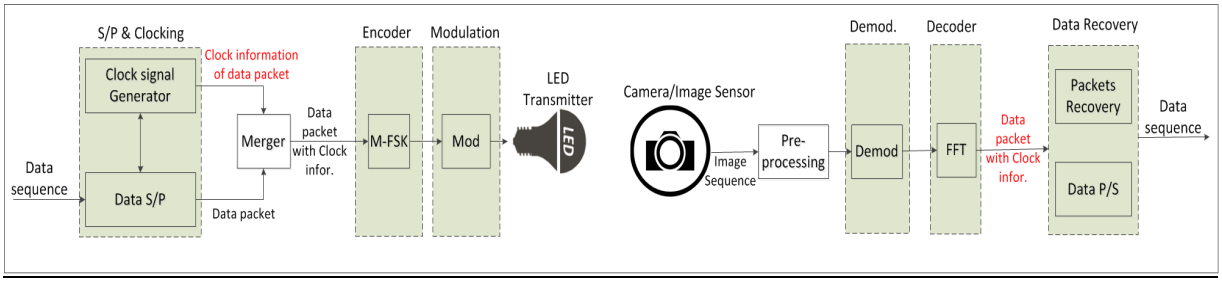


Figure 4: System Architecture for clock transmission approach in frequency domain

Definition

- **clock information (of a data packet)**: This scheme is similar to the C-OOK scheme in which asynchronous bits (Ab) represent the form of clock information. However, the data packet with clock information (called a symbol) is encoded using M-FSK technique.
- **Frequency symbol**: a symbol modulated by a frequency to transmit a data packet

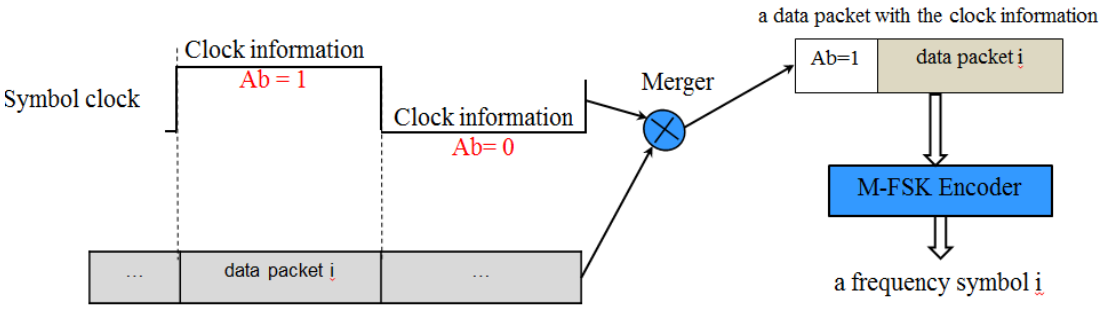


Figure 5: Data and clock information merging in frequency domain

FFT:

- The peak value of the FFT spectrum is linear proportional to the modulation frequency of light

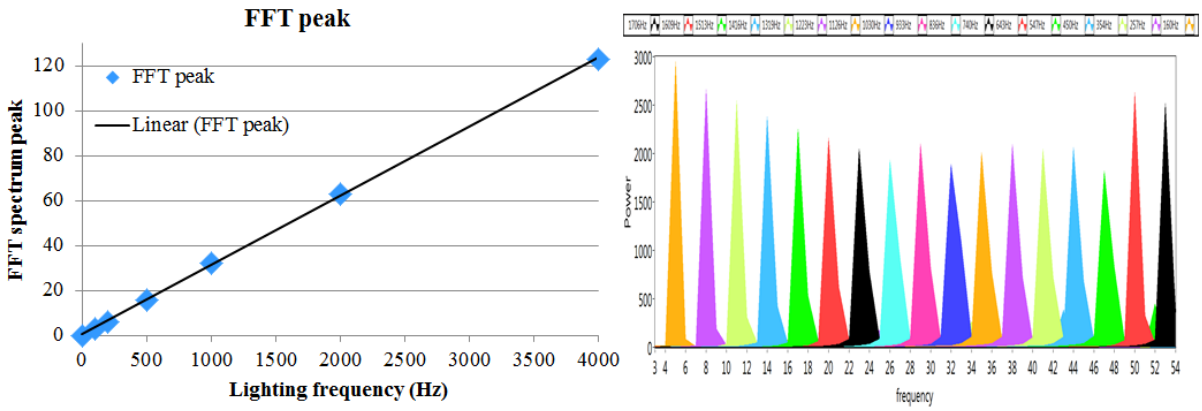


Figure 6: Spectrum peak and the corresponding frequency measurement

2.2 PHY asynchronous transmission method

2.2.1 C-OOK asynchronous transmission

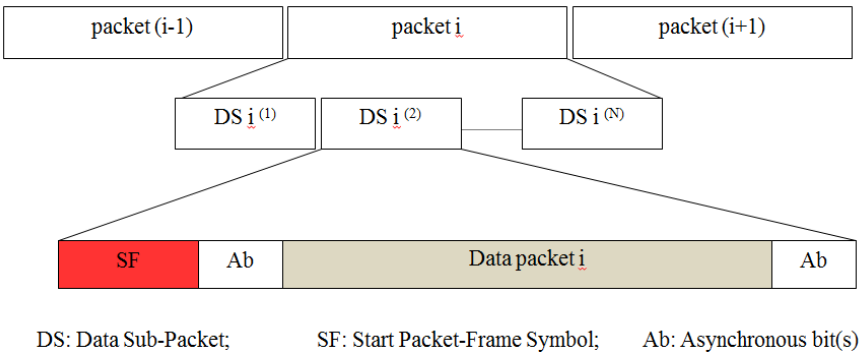


Figure 7: Data Packet Structure

Data packet Structure:

- A packet is multiple times repeat of one data symbol.
- A complete DS has a very-low-header symbol (SF), two similar asynchronous bits (which is a form of the *clock information*)

Table: Definition of SF symbol (Preamble symbol)

SF symbol (preamble)	Ab	Data	Ab
011100	bit 1/0	Manchester coding	bit 1/0
0011111000		4B6B coding	
000011111111100000		8B10B coding (withdraw)	

Definition of SF symbol (preamble):

- A **SF symbol** is **easily distinguished** among data symbols. When the frame rate is varying irregularly, the position of the SF symbol on the rolling image is also varying. The detection of SF becomes indispensable for the decoding (forward and backward parts) and recovering data.
- The length of SF is different for each RLL code (in order to be **low-overhead** and detectable).

Note:

- After proposal in January, we decide to withdraw 8B10B coding to reduce complexity in system implementation. The first page showed our final decision of PHY modes.
- For this PHY 5, the PHY header shall be sent at optical clock rate 2.2kHz or 4.4kHz. Support for 2.2kHz optical clock rate is mandatory.

2.2.1.1 Asynchronous Decoding: Rolling exposure time >> (DS interval)

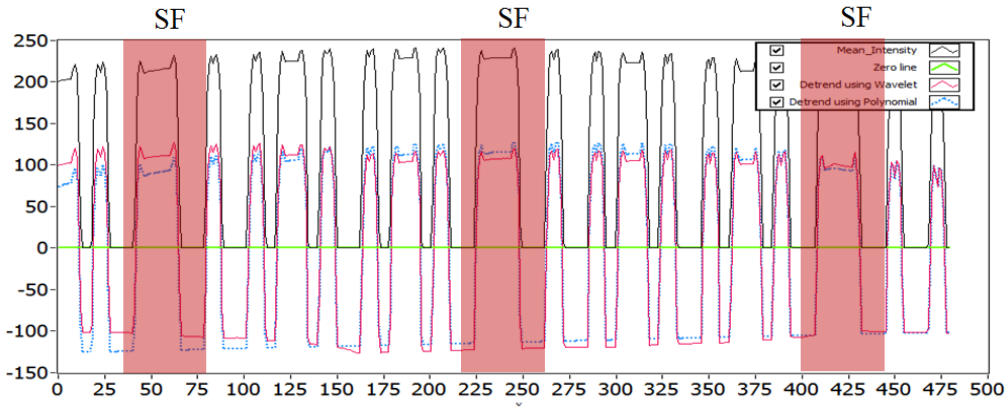


Figure 8: Decoding case 1

Decoding case 1: Oversampled Asynchronous decoding

- This happens when the DS interval is short to be compatible to different rolling exposure times
- The *majority voting* is applied between several images or within an image (using asynchronous bits) to enhance BER.

2.2.1.2. Asynchronous Decoding: Rolling exposure time ~ (DS interval)

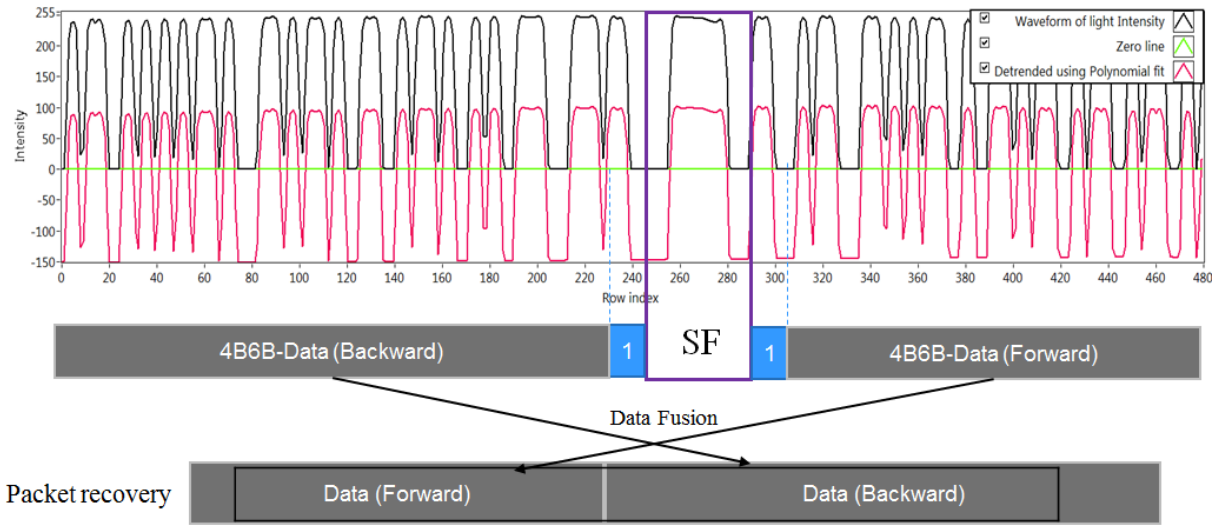


Figure 9: Decoding case 2

Decoding case 2: Forward decoding and Backward decoding

- When the rolling exposure time is almost equal to DS interval, forward and backward are both used to get 100% information of an image.
- The fusion of forward part and backward part (of a data packet) is performed to output a complete data packet.

2.2.1.3 Packet Recovery

❑ ***Two cases may happen at different sampling time:***

- Case 1- *Inter-frame data fusion*: Fusing two sub-parts of a packet at two different images into a complete packet.
- Case 2- *Intra-frame data fusion*: Recovering a complete packet from an image.

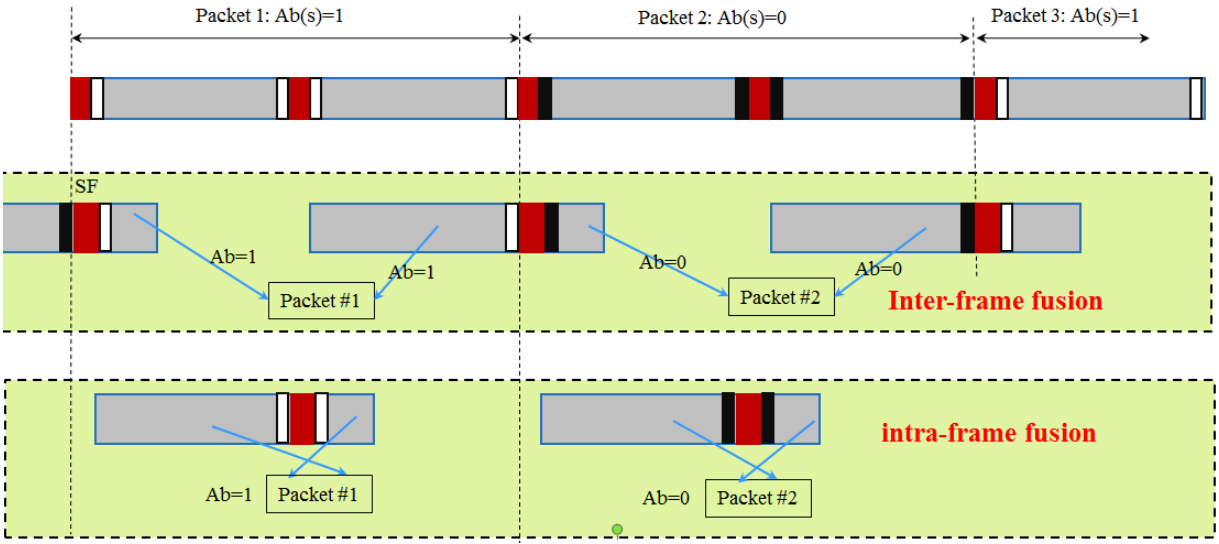


Figure 10: Packet recovery

2.2.2 *CM-FSK asynchronous transmission*

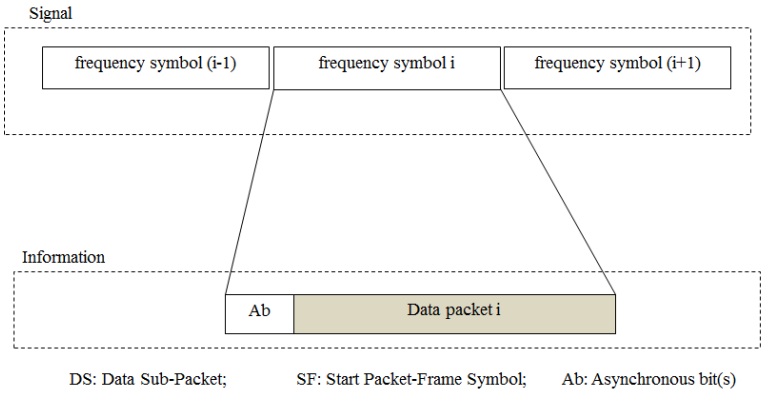


Figure 11: Data packet structure

- **A frequency symbol** is hold a duration to transmit a data packet
- An asynchronous bit (represents the clock information of the data packet) is along with the packet in transmission.

Frequency band:

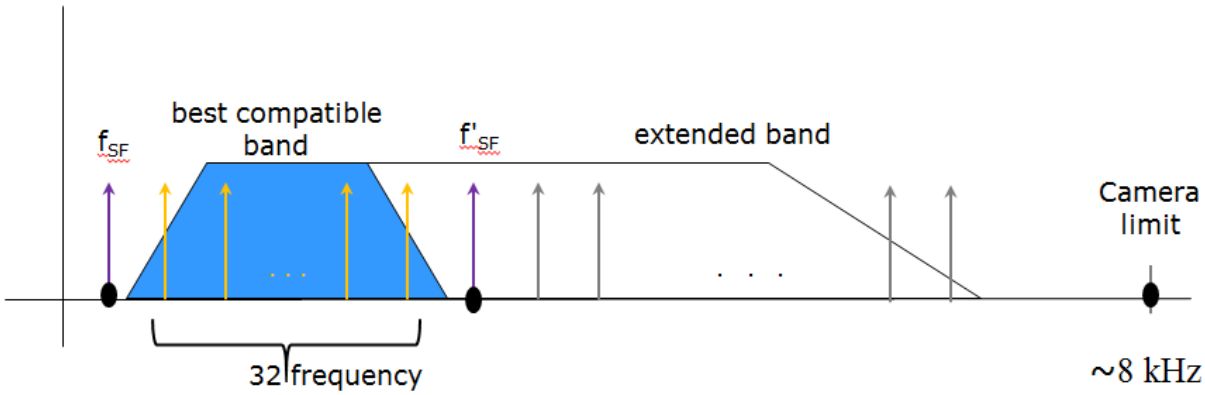


Figure 12: Frequency band in use

32-FSK Modulation

Symbol structure

bits: 1	4
Ab	Data packet

C32-FSK encoding table

Baud symbol	Frequency
f_{SF}	**fo**
00000	f1
00001	f2
. . .	
11110	f_{31}
11111	f_{32}
f'_{SF}	f_{33}

- Data frequency: $f_i = f_{SF} + i.\Delta f$ (i=1; 2;…; 32)
- Preamble frequency: $f'_{SF} = f_{SF} + 33.\Delta f$

64-FSK Modulation

Symbol structure

bits: 1	5
Ab	Data packet

C64-FSK encoding table

Baud symbol	Frequency
f_{SF}	fo
000000	f_1
000001	f_2
. . .	
101110	f_{31}
101111	f_{32}
f'_{SF}	f_{33}
010000	f_{34}
010001	f_{35}
. . .	
111110	f_{64}
111111	f_{65}

Hybrid Frequency-Phase Shift Keying

- *Advantages of M-FSK:*
  - Support for multiple transmitters (LEDs). Frequency allocation is based on M-FSK to share the bandwidth to all LEDs. The M-FSK technique is to avoid interference efficiently.
  - Great support for rolling shutter receivers. The detection of frequency is much easier with rolling effect.
- *Additional advantage of N-PSK:*
  - The N-PSK is additionally used to achieve higher data rate than just M-FSK. The higher link rate is helpful when a part of link rate must be shared for mitigating frame rate variation (by transmitting the asynchronous bits instead of data).
  - Additionally support for global shutter receivers (only 2-PSK, optional).

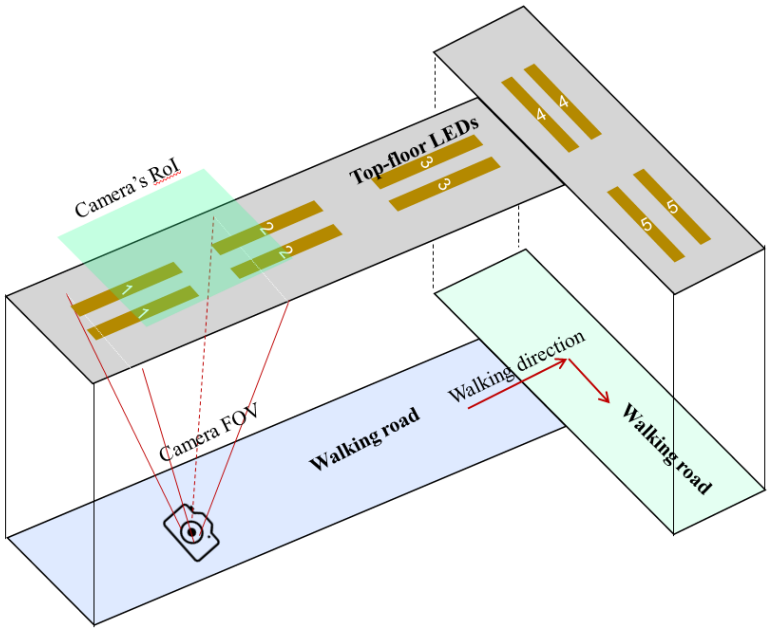


Figure 13: **Hybrid modulation scheme: LEDs lighting design**

2.3 PHY dimming method

2.3.1 C-OOK dimming

The definition of LED state 0 and 1 does not required to be totally turned off and on. The dimming is performed by amplitude modulation (AM).

2.3.1 M-FSK dimming

Pulse Width Modulation (PWM) is applied to dim the light.

3. PHY 5 frame

3.1. PPDU format and superframe format

3.1.1. Super frame

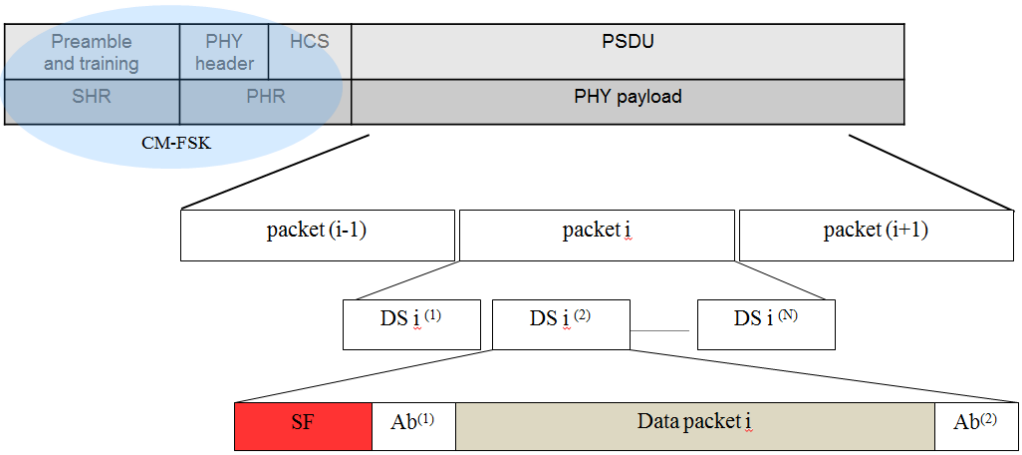


Figure 14: Format of the PPDU

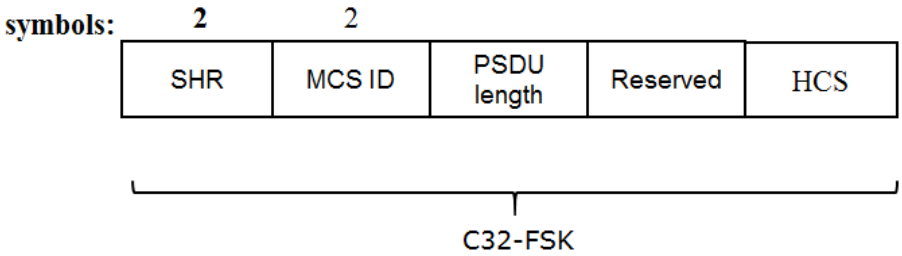


Figure 15: SHR and PHR frame structure

Data frequency: $f_i = f_{SF} + i.\Delta f$ (i=1; 2;…; 32)
Preamble frequency: $f'_{SF} = f_{SF} + 33.\Delta f$

3.1.2 OOK PPDU frame

3.1.2.1 Frame type 1: Short frame and non-error detection

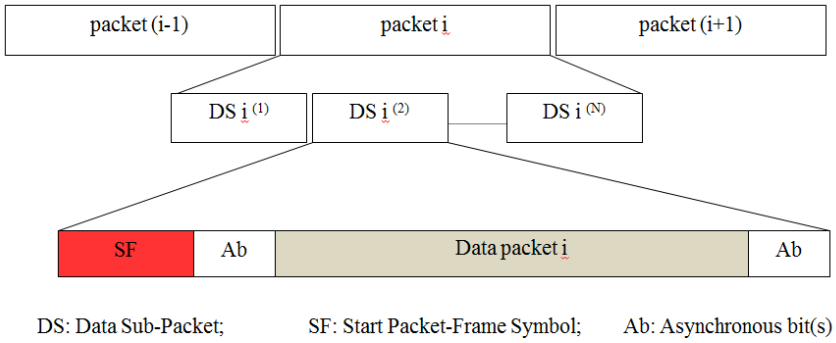


Figure 16: Data Packet Structure using a single Ab before and after data part.

Our recommendation 1 of parameters:

Manchester			
3 bit	8 bit		
SF	Ab	Data	Ab
OOK: 6	2	8	2

Manchester code (short frame mode)	
Frequency	2.2 kHz
DS Packet rate	100 DS/s
Symbol rate	10 symbol/s
PHY SAP data rate	60 bps

Operation recommendation:

* Frame rate: > 10 fps
* Exposure time: > 10% of (image-frame interval)

Our recommendation 2 of parameters:

4B6B			
6.67	17 bit		
SF	Ab	Data	Ab
OOK: 10	26		

4B6B code (long frame and none-error detection mode)	
Frequency	2.2 kHz
DS Packet rate	60 DS/s
Symbol rate	10 symbol/s
PHY SAP data rate	150 bps

Operation recommendation:
* Frame rate: > 10 fps
* Exposure time: > 16.7% of (image-frame interval)

3.1.2.2 Frame type 2: Long frame with missing frame (error) detection

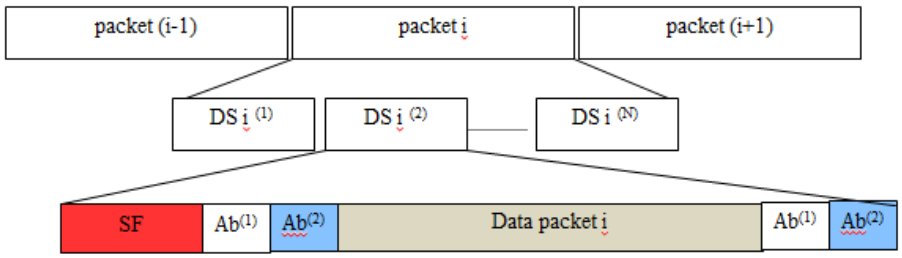


Figure 17: Data Packet Structure using couple Ab before and after data part

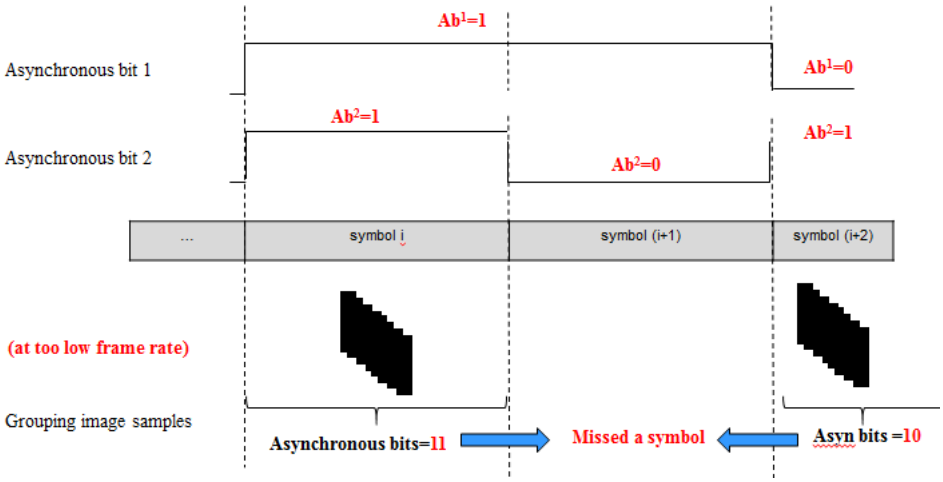


Figure 18: Detecting missing symbol using asynchronous bits

Our recommendation 3 of parameters:

Manchester			
3 bit	33 bit		
SF	Ab	Data	Ab
OOK: 6	4	24	4

Manchester code (long frame with error detection mode)	
Frequency	4.4 kHz
DS Packet rate	60 DS/s
Symbol rate	20 symbol/s
PHY SAP data rate	580 bps

Operation recommendation:

* Frame rate: > 20 fps. Any error caused by frame rate drops to less than 20fps can be detected and corrected
* Exposure time: > 33% of (image-frame interval)

Our recommendation 4 of parameters:

4B6B			
	41 bit		
SF	Ab	Data	Ab
OOK: 10	62		

4B6B code (long frame with error detection mode)	
Frequency	4.4 kHz
DS Packet rate	60 DS/s
Symbol rate	20 symbol/s
PHY SAP data rate	70 bps

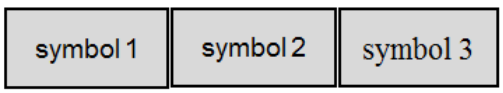
Operation recommendation:

* Frame rate: > 20 fps. Any error caused by frame rate drops to less than 20fps can be detected and corrected
* Exposure time: > 33% of (image-frame interval)

3.1.3 FSK PPDU frame

Table: M-FSK modulation of a PPDU frame

32-FSK	64-FSK
Symbol structure bits: 1 | 4 Ab | Data packet	**Symbol structure** bits: 1 | 5 Ab | Data packet



Symbol structure

bits: 1	4/5
Ab	Data packet

Figure 19: PPDU frame

3.2. PHY attributes

PHY PIB Table 100 Additions				
Attribute	**Identifier**	**Type**	**Range**	**Description**
phyOccProposerID	3 bit	Integer	0-8	
phyOccApplicationSpecificMode	k bit	Integer	0-N	

Table: OCC Proposer ID

PIB Attribute Value	Proposer
0	Intel
1	Panasonic
2	Kookmin
…	
7	…

Table: OCC Application Specification PHY Specific Mode

PIB Attribute Value	Mode name	Mode
0	Kookmin RS-OOK Mode 1	Manchester coding Oversampling & short frame mode
1	Kookmin RS-OOK Mode 2	4B6B coding Oversampling & long frame mode
2	Kookmin RS-OOK Mode 3	Manchester coding Error detection & long frame mode
3	Kookmin RS-OOK Mode 4	4B6B coding Error detection & long frame mode
4	Kookmin RS-FSK Mode 1	M-FSK 32 frequency mode
5	Kookmin RS-FSK Mode 2	M-FSK 32-frequency & 2-Phase + FEC mode
6	Kookmin RS-FSK Mode 3	M-FSK 64-frequency & 4-Phase + FEC mode
…		

4.0 MAC frame

4.1 MAC types

4.2 MAC frame formats

4.3 MAC PIB attributes

MAC PIB Table 60 Additions					
Attribute	**Identifier**	**Type**	**Range**	**Description**	**Default**
mac_symbol_rate			5-20	To adapt Tx symbol rate versus Rx frame rate variation when Rx has the minimum frame rate below the symbol rate.	10
mac_bandwith			2kHz – 8kHz	To adapt Tx frequency band versus Rx sampling rate when Rx has a low sampling rate that cannot get data in PSDU frames.	
mac_LEDs_spatial_resolution		int		To adapt the number of Tx LEDs spatially (resolution) versus Rx image resolution mode.	2
mac_DS_rate		int	60-120	To control the length of a data subframe. Shorter data frame can support for longer distance transmission.	100

Symbol rate: 10 symbol/sec or 20 symbol/sec

mac_LEDs_spatial_resolution: Default is 2 for S2-PSK by using dual LEDs (a left one and a right one; or a top one and a bottom one) to transmit an ID identifier that tells a receiver to map the real number of LEDs on the transmitter.

DS rate (for OOK scheme only): Short frame mode (100 DS/s) or Long frame mode (60 DS/s)