IEEE P802.15
Wireless Personal Area Networks

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6.6 PHY TYPE 1 specifications

The type 1 PHY is targetted towards applications requiring data rates operating at several tens of meters of range with data rates shown in Table 2.

6.6.1 Data rate

The LRP supports data rates of 6.25 kbps, 12.5 kbps, 25 kbps, 50 kbps and 100 kbps using OOK and 200 kbps and 400 kbps using VPM. The data rate of 6.25 kbps is used for link establishment. After the link is established other data rates may be utilized based upon the desired quality of service.

6.6.2 Reference modulator diagram

A reference implementation is shown in Figure 1.

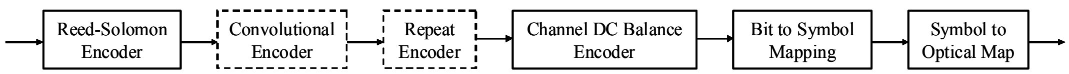


Figure 1—Reference modulator diagram

The blocks in dash lines are not used by all PHY TYPE 1 modes.

6.6.3 Outer Forward Error Correction Encoder

The outer FEC code shall be used by all PHY 1 modes and is a RS(15,12) code defined by the polynomial [TBD].

6.6.4 Inner Forward Error Correction Encoder

Not all PHY 1 modes use concatenated FEC. The following modes shall use an inner forward error correction code.

6.6.4.1 200 kbps VPMand 50 kbps OOK

[Ed. Note - is the 200 kbps VPM FEC 1/2 rate convolutional coding?]

These modes shall use 1/2 rate convolutional code with constraint length k=7 and octal generator polynomials, g0 = 133 and g1 = 171.

6.6.4.2 25 kbps OOK

These modes shall use 1/4 rate convolutional code with constraint length k=7 and octal generator polynomials, g0 = 135, g1 = 135, g2=147 and g3=163.

6.6.4.3 12.5 kbps OOK

These modes shall use 3/8 rate convolutional code. This code is derived from a 1/3 rate convolutional code with constraint length k=7; octal generator polynomials g0 = 133, g2=145 and g1 = 175; and the punction pattern as shown if Figure 2.

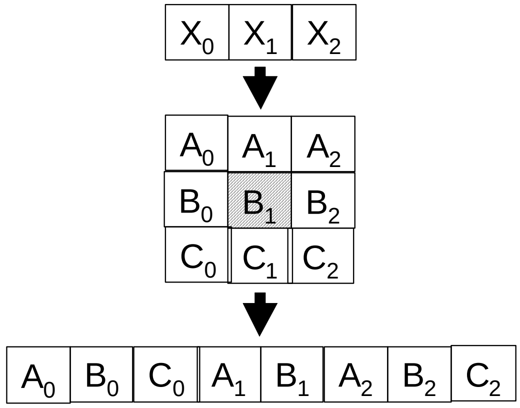


Figure 2—Puncture pattern for 3/8 rate coding

6.6.4.4 6.25 kbps OOK

These modes shall use 5/16 rate convolutional code. This code is derived from a 1/4 rate convolutional code with constraint length k=7; octal generator polynomials g0 = 135, g1 = 135, g2=147 and g3=163; and the punction pattern as shown if Figure 3.

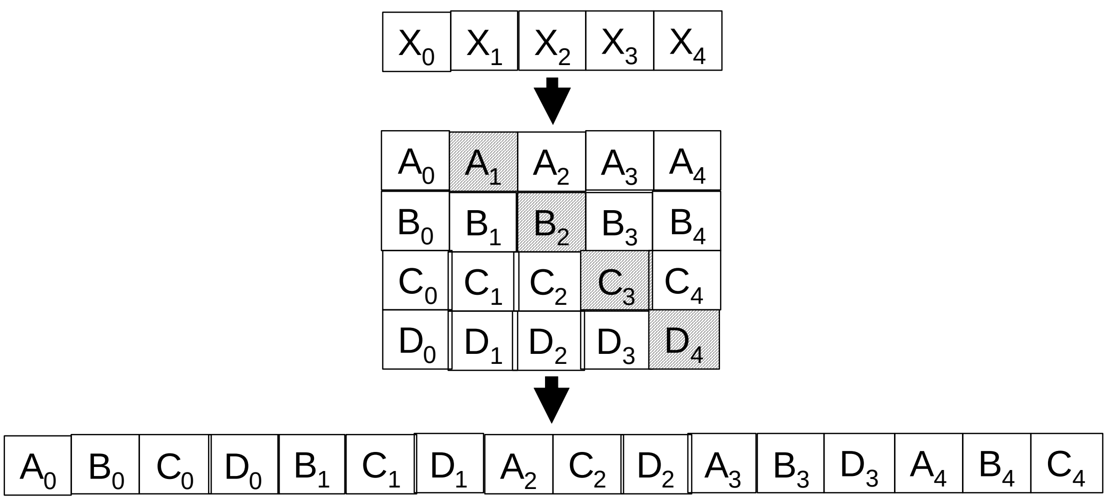


Figure 3—Puncture pattern for 3/8 rate coding

6.6.5 Repeat Encoder

The following modes shall use repeat coding.

6.6.5.1 12.5 kbps OOK

This mode shall repeat each convolutional coded bit 3 times.

6.6.5.2 6.25 kbps OOK

This mode shall repeat each convolutional coded bit 5 times.

6.6.6 Channel DC Balancing Encoder

6.6.6.1 VPM modes

All VPM PHY 1 modes shall use 4B6B DC balancing encoding. The 4B6B expands 4-bits to 6-bit encoded symbols with 50% duty cycle. Table 1 defines the 4B6B code.

Table 1—Mapping input 4B to output 6B

4B	6B
0000	001110
0001	001101
0010	010011
0011	010110
0100	010101
0101	100011
0110	100110
0111	100101
1000	011001
1001	011010
1010	011100
1011	110001
1100	110010
1101	101001
1110	101010
1111	101100

6.6.6.2 OOK modes

All OOK PHY 1 modes shall use Manchester DC balancing encoding. The Manchester code expands each bit into an encoded 2-bit symbol as shown in Table 2.

Table 2—Manchester Encoding

bit	Manchester Symbol
0	01
1	10

6.6.7 Symbol to Optical Mapping

A logic level high applied to the light source shall result in a high radiated intensity. A logic level low applied to the light source shall result in a reduced radiated intensity.

6.7 PHY Type 2 specifications

The type 2 PHY is targetted towards applications requiring high data rates operating at several meters of range with data rates shown in Figure 3.

6.7.1 Data rate

This PHY supports data rates of 3.2 Mbps and 6.4 Mbps using VPM modulation and data rates of 9.6 Mbps, 24 Mbps, 38.4 Mbps, 76.8 Mbps and 96 Mbps using OOK modulation. The VPM data rate of 6 Mbps is used for link establishment [Ed. Note: what duty cycle is used for link establishment? 50%?]. After the link is established other data rates may be utilized based upon the desired quality of service.

6.7.2 Reference modulator diagram

A reference implementation is in Figure 4.

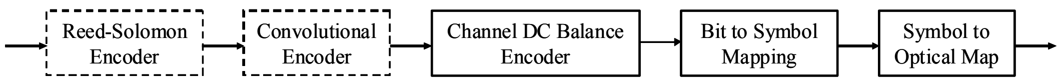


Figure 4—Reference modulator diagram

The blocks in dash lines are not used by all PHY TYPE 2 modes.

6.7.3 Forward Error Correction Encoder

6.7.3.1 All VPM modes and 38.4 Mbps and 76.8 Mbps OOK

These modes shall use the Reed-Solomon code as defined in 6.6.3

6.7.3.2 9.6 Mbps and 24 Mbps OOK

[Ed. Note - is a 1/2 rate convolutional code used here?]

These modes shall use the 1/2 rate convolutional code defined in 6.6.4.1.

6.7.3.3 96 Mbps OOK

This mode shall not use FEC.

6.7.4 Channel DC Balancing Encoder

6.7.4.1 All VPM modes

All PHY 2 VPM modes shall use 4B6B DC balancing coding as defined in 6.6.6.1.

6.7.4.2 All OOK modes

All OOK PHY 2 modes shall use 8B/10B DC balancing code as specified in ANSI/INCITS 373: Fiber Channel Framing and Signaling Interface (FC-FS), Clause 11. [Ed Note: Reference section needed]

6.7.5 Symbol to Optical Mapping

A logic level high applied to the light source shall result in a high radiated intensity. A logic level low applied to the light source shall result in a reduced radiated intensity.

6.8 CSK PHY specifications

6.8.1 Data rate

The standard shall support CSK in support of multiple applications with data rates from 12 Mbps to 96 Mbps as shown in Table 4. The CSK mode shall use [Ed. Note: what?] for link establishment after which an alternate data rate may be used for ensuring data communications.

6.8.2 Reference modulator diagram

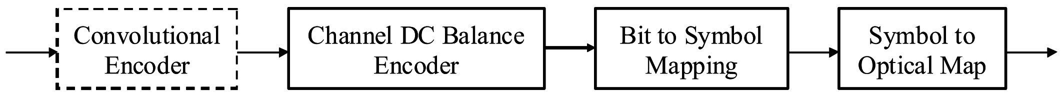


Figure 5—Reference modulator diagram

The blocks in dash lines are not used by all the CSK PHY types.

6.8.3 Forward Error Correction Encoder

Not all CSK modes use forward error correction. The 72 Mbps and 96 Mbps modes shall not utilize forward error correction. The remaining modes, namely the 12 Mbps, 18 Mbps, 24 Mbps, the 36 Mbps and the 48 Mbps modes shall use 1/2 rate convoluational coding [Ed Note: is it really convoluational coding or is it a Reed-Solomon code?] as defined in 6.6.4.1.

6.8.4 Channel DC Balancing Encoder

All CSK modes use the 8B10B DC balancing code as defined in 6.7.4.2.

6.8.5 CSK bit to symbol mapping

[Ed Note: the following text is not a specification - it is a tutorial. Specification text needs to be supplied that distinctly indicates how bits are mapped to CSK symbols].

Figure 6 shows the proposed color constellation for the CSK.

4CSK can send 2bits per symbol. 8CSK can send 3bits per symbol. 16CSK can send 4bits per symbol.

Those color constellations were decided for having same and max distance from adjacent symbols.

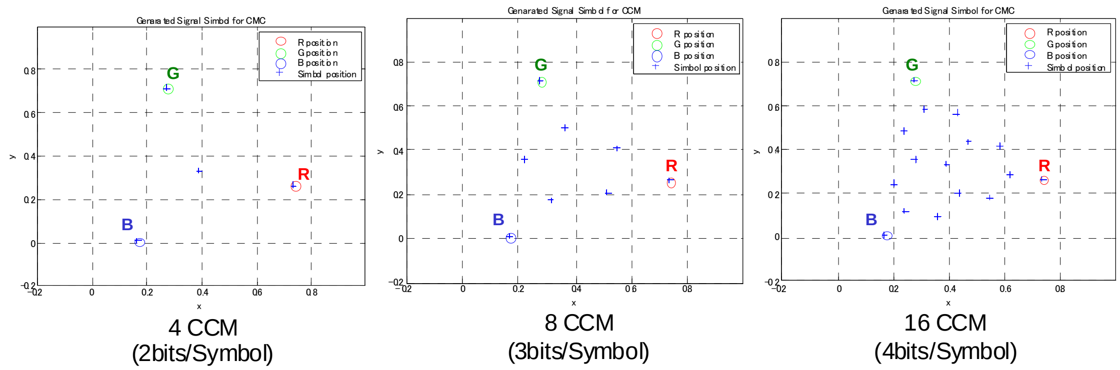


Figure 6—Color constellations for CSK

6.8.6 Symbol to Optical Mapping

[Ed. Note: how do we map the CSK symbol to the optical sources? Are the optical sources 3 color RGB? Can it be another 3 colors? How do we determine the proper intensity for the optical sources so as to realize the color point in the CSK constellation?]

6.8.7 CSK Calibration

[Ed Note: we did definitive text on how the calibration signal is generated at the transmitter and then informative text on how the receiver utilizes this information.]

VLC system could have some degradation, for example, multi-color imbalance, multi-color interference or other error on xy color coordinates caused by ambient light or own light device characteristics. Therefore, we have to prepare CSK compensation method.

CSK calibration is proposed for solving the problem.

In Figure [TBD - where is this figure?], the system estimates the channel propagation matrix using orthogonal sequence (ex. Walsh code) included in the header of the frame.

Data symbols are compensated by using the estimated channel matrix. It is similar as MIMO algorithm on radio systems.

6.9 General radio specifications

6.9.1 TX-to-RX turnaround time

The TX-to-RX turnaround time shall be less than *aTurnaroundTime* (see 6.5.1).

The TX-to-RX turnaround time shall be measured at the air interface from the trailing edge of the last transmitted symbol until the receiver is ready to begin the reception of the next PHY packet.

6.9.2 RX-to-TX turnaround time

The RX-to-TX turnaround time shall be less than aTurnaroundTime (see 6.5.1).

The RX-to-TX turnaround time shall be measured at the air interface from the trailing edge of the last chip (of the last symbol) of a received packet until the transmitter is ready to begin transmission of the resulting acknowledgment. Actual transmission start times are specified by the MAC sublayer (see [TBD reference]).

6.9.3 Error-vector magnitude (EVM) definition

The modulation accuracy of an IEEE 802.15.7 transmitter is determined with an EVM measurement. In order to calculate the EVM measurement, a time record of N received complex chip values is captured. For each received chip, a decision is made about which chip value was transmitted. The ideal position of the chosen chip (the center of the decision box) is represented by the vector . The error vector is defined as the distance from this ideal position to the actual position of the received point (see Figure 7).

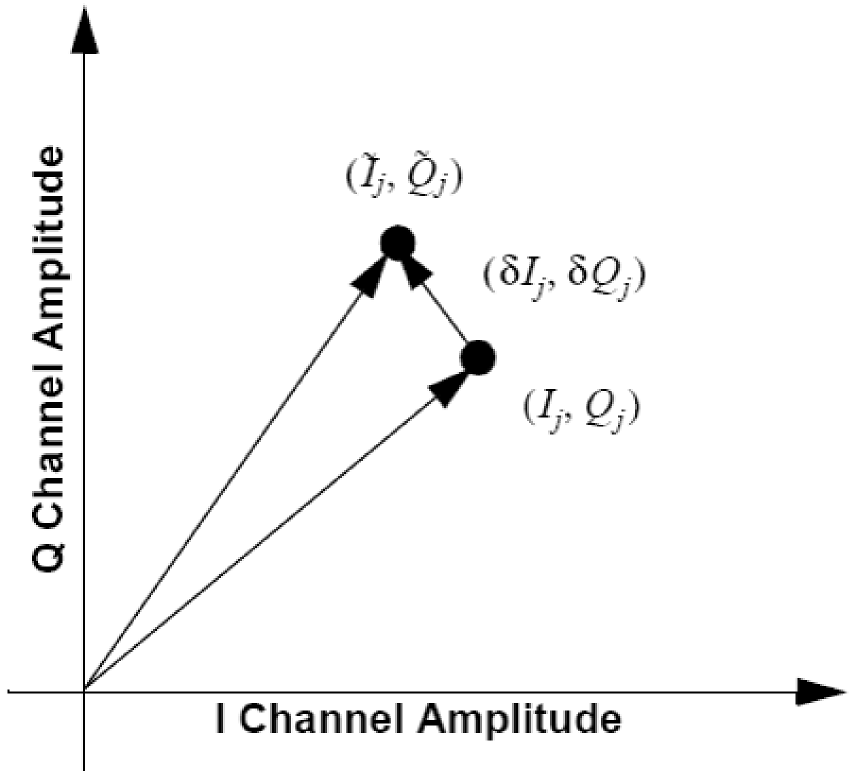


Figure 22—Error vector calculation

Figure 7—Error vector calculation

NEED TO FINISH THIS SECTION - WE SHOULD SPECIFY AN ERROR VECTOR MAGNITUDE FOR OOK/VPM. ARE WE GOING TO DO THIS FOR CSK?

6.9.3.1 EVM calculated values

An IEEE 802.15.7 transmitter shall have EVM values of less than [TBD]% when measured for 1000 chips. The error-vector measurement shall be made on baseband I and Q chips after recovery through a reference receiver system. The reference receiver shall perform carrier lock, symbol timing recovery, and amplitude adjustment while making the measurements.

6.9.4 Transmit frequency tolerance

The transmitted frequency tolerance shall be ± [TBD] ppm maximum.

6.9.5 LQI

6.9.5.1 OOK and VPM

The LQI measurement is a characterization of the strength and/or quality of a received packet. The measurement may be implemented using receiver ED, a signal-to-noise ratio estimation, or a combination of these methods. The use of the LQI result by the network or application layers is not specified in this standard.

The LQI measurement shall be performed for each received packet, and the result shall be reported to the MAC sublayer using PD-DATA.indication (see 6.2.1.3) as an integer ranging from 0x00 to 0xff. The minimum and maximum LQI values (0x00 and 0xff) should be associated with the lowest and highest quality IEEE 802.15.7 signals detectable by the receiver, and LQ values in between should be uniformly distributed between these two limits. At least eight unique values of LQ shall be used.

6.9.5.2 CSK Color Quality Indicator support

A device shall be capable of estimating the link quality of the received color channel, where the color quality shall be defined as an estimate of the SNR available after the CDR and will include all implementation losses associated with that particular receiver architecture (quantization noise, channel estimation errors, etc.). All estimated values, when measured under static channel conditions, shall be monotonically increasing with signal strength over the entire reporting range. Note that the estimates may exhibit saturation behavior at values higher than that required for highest data rate operation. Finally, the link quality estimates shall be made on a packet-by-packet basis. No bounds on absolute accuracy with respect to an external reference plane are intended or implied by this specification.

6.9.6 CCA

The IEEE 802.15.7 PHY may provide the capability to perform CCA according to at least one of the following three methods:

— CCA Mode 1: Energy above threshold. CCA may report a busy medium upon detecting any energy above the energy detect threshold.

— CCA Mode 2: Carrier sense only. CCA may report a busy medium only upon the detection of a signal with the modulation characteristics of IEEE 802.15.7. This signal may be above or below the energy detect threshold.

— CCA Mode 3: Carrier sense with energy above threshold. CCA may report a busy medium only upon the detection of a signal with the modulation characteristics of IEEE 802.15.7 with energy above the energy detect threshold.

For any of the CCA modes, if the PLME-CCA.request primitive (see 6.2.2.1) is received by the PHY during reception of a PPDU, CCA may report a busy medium. PPDU reception is considered to be in progress following detection of the SFD, and it remains in progress until the number of octets specified by the decoded PHR has been received.

A busy channel may be indicated by the PLME-CCA.confirm primitive (6.2.2.2) with a status of BUSY.

A clear channel may be indicated by the PLME-CCA.confirm primitive (6.2.2.2) with a status of IDLE.

The PHY PIB attribute phyCCAMode (see 6.5) may indicate the appropriate operation mode. The CCA parameters are subject to the following criteria:

a) The energy detect threshold may be at most [TBD] dB above the specified receiver sensitivity (see 6.1.7).

b) The CCA detection time may be equal to [TBD] symbol periods.

6.9.7 Dimming

A compliant 802.15.7 device shall support dimming using one of the techniques specified in either Clause 6.9.7.1, Clause 6.9.7.2, Clause 6.9.7.3 or Clause 6.9.7.4.

6.9.7.1 Explicit Visible/Dimming pattern

The possible Visible Pattern codes that can be used in the Visible Pattern field are shown in Figure 8 The code used in the Visible Pattern field is the code specified in the Visible Frame Pattern field of the Control Header field repeated throughout the Visible Pattern field.

We define a set of 11 base visibility patterns based on the 8b10b code to ensure there is no conflict between the visibility pattern and the data transmission at the receiver. We use these base patterns in order to generate high resolution patterns.

Visibility pattern (Percentage visibility)
11111 11111 (100%)
11110 11111 (90%)
11110 11110
11101 11100
11001 11100
10001 11100
00001 11100
00001 11000
00001 10000
00001 00000 (10%)
00000 00000 (0%)

Figure 8—Visibility Patterns

In order to generate high resolution visibility patterns, there are certain constraints that need to be used in the design criteria.

- The number of transitions between 0's and 1's must be maximized to provide high frequency switching in order to avoid flicker and to help the CDR circuit at receiver for synchronization purposes, if used.

- Current visibility patterns proposed can have certain properties (visible pattern does not match any existing data pattern out of the 8b10b code). These properties must be preserved with new high resolution patterns.

- Designing a thousand patterns to support low resolutions (as low as 0.1% resolution) is not practical and makes visibility pattern generation and use very complex.

We use existing low resolution patterns to develop high resolution visibility patterns by combining them in multiple ways to generate the required high resolution pattern. For example, if visibility patterns are available at 10% resolution, then a 25% visibility pattern can be attained for example, by alternately sending a 20% visibility pattern followed by a 30% visibility pattern. This method guarantees all frames will retain the same properties as existing visibility frames However, there are multiple ways in which this can be achieved. We provide an algorithm to use at the transmitter to attain the desired visibility. This provides the duty cycle for the visibility required in the shortest amount of time while maximizing the number of transitions and minimizing flicker.

• Dimming or visibility levels: $V_0, V_1, \ldots, V_K$ ($V_0 = 0\%, V_K = 100\%$)

• Desired visibility for dimming = dv (percentage)

• Desired precision = p, $p \leq 0, p \in Z$

Algorithm:

$$\text{sel1pat} = \left\lfloor \frac{dv * K}{100} \right\rfloor$$

$$\text{sel2pat} = \left\lceil \frac{dv * K}{100} \right\rceil$$

$$\text{reppat2} = 10^{-p}\left(dv - \frac{100 * \text{sel1pat}}{K} \right)$$

$$\text{reppat1} = 10^{1-p} - \text{reppat2}$$

repeat V_{sel1pat} reppat1 times

repeat V_{sel2pat} reppat2 times

Figure 9—Generating high resolution visibility patterns

6.9.7.2 VPM Dimming

The VPM PHY will have basic dimming level support at 10% duty cycle resolution (note: for ease of implementation). To support higher resolution for dimming, the VPM PHY shall use the same algorithm as that mentioned for the in-band visibility pattern mentioned below. For example, for supporting 25% dimming, the VPM PHY shall alternately send 20% and 30% duty cycle symbols.

6.9.7.3 CSK Dimming

In CSK, total power of multiple light sources is constant. For dimming control, the total power of the multiple light sources is changed. CSK keeps the center color of the color constellation with required intensity instead of the idle pattern shown in clause 6.9.8

- Dimming or visibility levels: $V_0, V_1, \ldots, V_K$ ($V_0 = 0\%$, $V_K = 100\%$)
- Desired visibility for dimming = dv (percentage)
- Desired precision = p, $p \le 0$, $p \in Z$

Algorithm:

$$\mathrm{sel1pat} = \left\lfloor \frac{dv * K}{100} \right\rfloor$$

$$\mathrm{sel2pat} = \left\lceil \frac{dv * K}{100} \right\rceil$$

$$\mathrm{reppat2} = 10^{-p}\left(dv - \frac{100 * \mathrm{sel1pat}}{K} \right)$$

$$\mathrm{reppat1} = 10^{1-p} - \mathrm{reppat2}$$

repeat V_{sel1pat} reppat1 times

repeat V_{sel2pat} reppat2 times

6.9.7.4 PHY Type Independent Dimming

Light dimming is generally a MAC layer function; however, it does require that the PHY periodically turn off the light source. The details are shown in 7.4.11

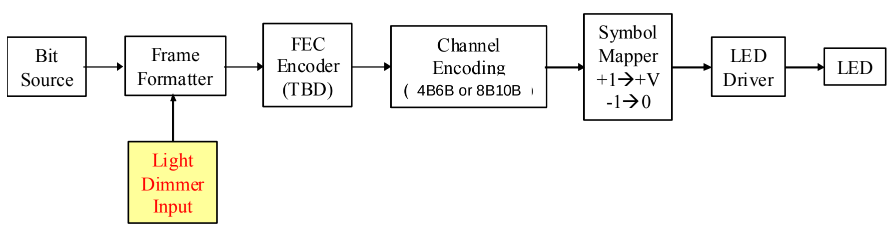


Figure 10—Lighting Dimming Model

OFF time is inserted into either the idle pattern or into the data frame, as shown below, to reduce the average intensity of the light.

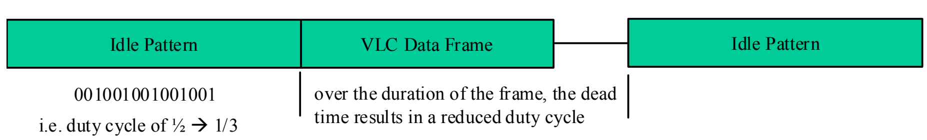


Figure 11—Flicker compensation

6.9.7.4.1 Idle Pattern Extinction Ratio

The extinction ratio ideally should be 100% but practically it can be as large as possible.

[Ed. Note: based upon the discussion from 09-0795-00 from Doug, the above statement is probably not true! Need to modify this accordingly.]

6.9.7.4.2 Filler Bit Pattern

The bit pattern used for the filler sequence shall be a repetitive 1010. The ratio of ones and zeros shall be adjusted so as to make the required dimming as per 6.9.7.4. The number of bits in the fillter pattern shall be an even number so as to maintain a DC balance on this sequence. The extinction ratio used for the transmission of the filler sequence shall be the same used for actual data packets.

6.9.7.4.3 Filler Bit Rate

The filler sequence shall be sent with a bit rate that is approximately [TBD] bps.

6.9.8 Frame Flicker Compensation (Informative)

Flickering of illumination is a harmful for human eyes. Some modulations make a flickering. Flickering defines an unexpected and unpredictable light intensity change recognized by human eyes. The flickering causes from a repetition of lighting on and off or slow change of brightness in a time period. There is a flickering in VLC lower data rate than 200 bps. Human eye can recognize the light status of on or off from light source. Some data pattern like long sequence of 1 or 0 produce off time and on time repeatedly.

0000 0001 0101 0111 1111 1110 1010 1000 0000

Maximum Flickering Time Period (MFTP) is a period that light intensity can be changed, but that cannot be recognized the change of brightness by human eyes;

MFTP: 1/minimum flickering free frequency (200Hz) = 5ms

To avoid a flickering from VLC, a brightness of each MFTP must be all equal. There are needed a flickering definition and MFTF (Max Flickering Time Period) by VLC or human eye safety regulation.

A solution for flickering removal is that we make a ratio of positive and negative level per MFTP to be constant with constant-weight code such as Manchester code, 2 PPM, and 4PPM. Manchester code has 50% duty cycle always. 2 PPM is 50% and 4 PPM is 25%. If we use this line code or modulation scheme for data stream and at idle time we use same waveform, flickering will not occur. But if we use NRZ OOK, we need another solution. Second solution is we make a ratio of 1 and 0 per MFTP to be constant at data stream.

To prevent the LED from appearing “dimmer” during the packet frame transmission time, an idle pattern is sent between frames that has the same duty cycle as the modulated frame but the pulse repetition rate (exact repetition rate is TBD) is set much lower so as not to cause “in band” interference with any VLC modulation.

Annex AVPM Principles (informative)

There are main three factors that are non-flickering, dimming control, and full brightness in VLC modulation scheme for illumination.

A flicker LED light due to VLC modulation is not good for eye safety. We need a modulation to remove the flicker for eye safety. If we cannot remove the flicker in VLC for illumination, no one use a VLC as an illumination.

LED illumination can control brightness with a dimming scheme. The dimming function is a mandatory for LED illumination. There are needed a modulation to support the dimming control function of LED light for VLC and illumination.

Full brightness is a primary function of LED illumination. A modulation of VLC might be decrease the brightness of LED illumination. There are needed a modulation to support full brightness in terms of illumination. It is desirable that VLC for illumination achieve the full brightness as much as LED light only for illumination do.

There are several candidates of VLC modulation as well as LED illumination. We can consider the modulation such as NRZ - OOK, RZ - OOK, PPM, I-PPM, PWM, and VPM.

NRZ-OOK(Non Return to Zero - On Off Keying) is one of the simple modulation scheme and a kind of amplitude-shift keying (ASK) modulation that represents digital data of "1" or "0" as the "on" or "off" states with non return to zero on off keying. Without line code, the flicker may be appeared. It is also difficult to achieve the dimming control and full brightness.

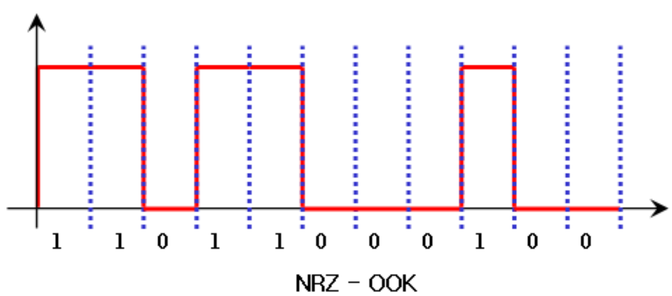


Figure 12—An example of NRZ-OOK

RZ-OOK(Return to Zero - On Off Keying) is one of the simple modulation scheme and a kind of amplitude-shift keying (ASK) modulation that represents digital data of "1" or "0" as the "on" or "off" states with return to zero on off keying.. Without line code, the flicker may be appeared. It is also difficult to achieve the dimming control and full brightness.

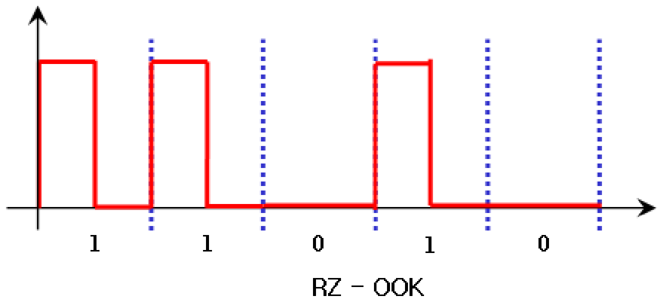


Figure 13—An example of RZ-OOK

PPM (Pulse Position Modulation) is that M message bits are encoded by transmitting a single pulse in one of 2M possible time-shifts. PPM is a good modulation for the non-flickering. But, it is difficult to achieve the dimming control and full brightness.

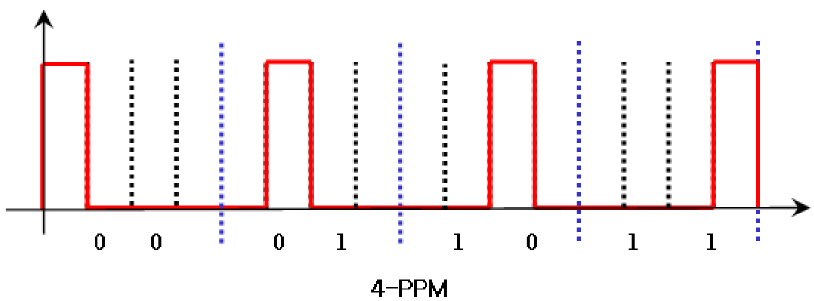


Figure 14—An example of PPM (Pulse Position Modulation)

I - PPM (Inverse - PPM) is that M message bits are encoded by transmitting a single pulse in one of 2M possible time-shifts. I-PPM is a good modulation for the non-flickering and the full brightness. But it is difficult to achieve the dimming control.

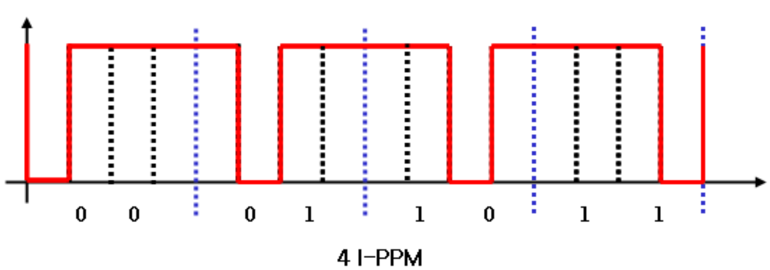


Figure 15—An example of I-PPM (Inverse Pulse Position Modulation)

PWM (Pulse Width Modulation) is the modulation scheme widely used in LED illumination for itself. So, we can basically achieve the flicker-free, the dimming control, and the full brightness by using PWM. If we use PWM only itself for VLC, we cannot obtain the flickering-free, the dimming control, or the full brightness.

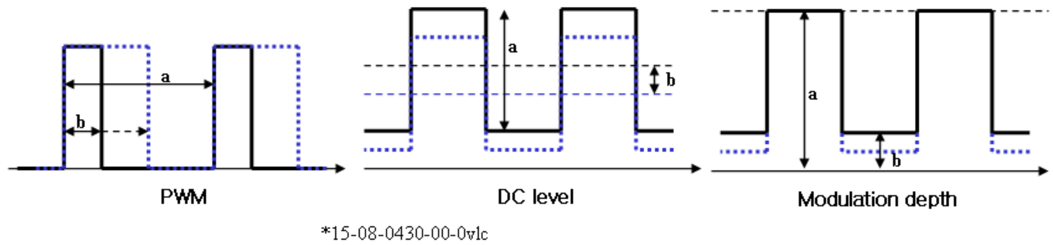


Figure 16—An example of PWM (Pulse Width Modulation)

VPM (Variable PPM) provides three main functions of illumination: non-flickering, dimming control, and full brightness. The basic concept of VPM is a combination of PWM and 2-PPM. 2-PPM(Pulse Position Modulation) provides a function without flickering. PWM (Pulse Width Modulation) provides a brightness control using duty cycle control. VPM equals to 2-PPM when the duty of VPM is 50 %.

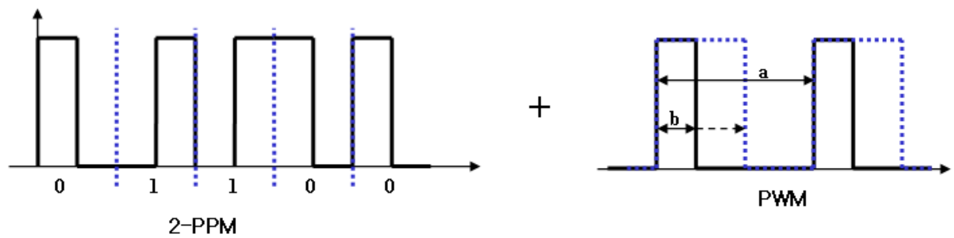


Figure 17—The basic concept of Variable PPM

We make an example waveform of proposed VPM with 75 % duty cycle. As you can see, In VPM, the flicker is free because the "on" state area is constant (same ratio) during each time period.

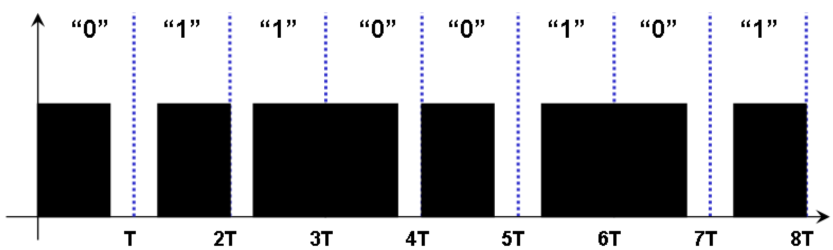


Figure 18—Example Waveform of Proposed VPM with 75% duty

We can make the VPM waveforms showing dimming control according to duty cycle. VPM provides the dimming control by adjusting the duty and the full brightness by increase of duty cycle resolution.

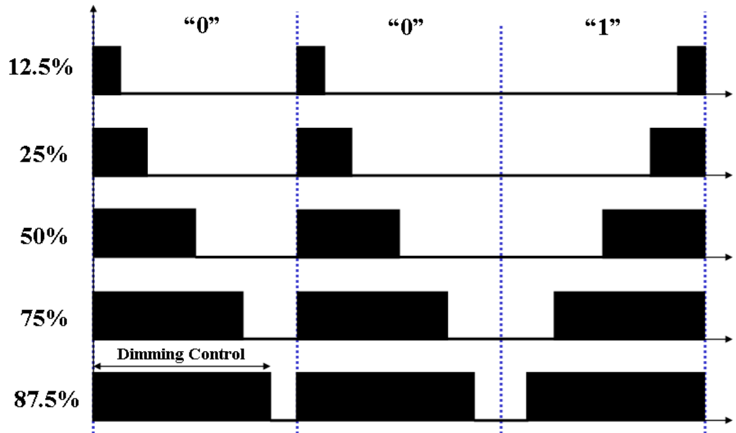


Figure 19—An example of dimming control by VPM signal

VPM provides both functions of illumination and communications with non-flickering, dimming control, and full brightness. VPM does not need a line code scheme for flicker-free signal. VPM is that the "on" state area of LED light is always constant under the given duty cycle. The dimming control of VPM can be provided by the duty cycle adjustment. The full brightness of VPM can be provided by the increase of the duty cycle resolution.

Annex BCSK principles (informative)

CSK assumes multi color light sources and photo detectors in a manner similar to WDM.

1) Connectivity is guaranteed by the color coordinates

CSK channels are decided by mixed colors that are allocated in the color coordinates plane. Therefore, the connectivity is guaranteed by the color constellation on the xy color coordinates.

2) Total power is constant

In CSK concept, the total power of all light sources is constant; therefore, the envelope of the sum of all light signals is constant.

3) Variable bit rate

In OOK case, the raw bit rate (code rate=1) is decided by just the symbol rate. That means OOK bit rate limited by the frequency response of the LED.

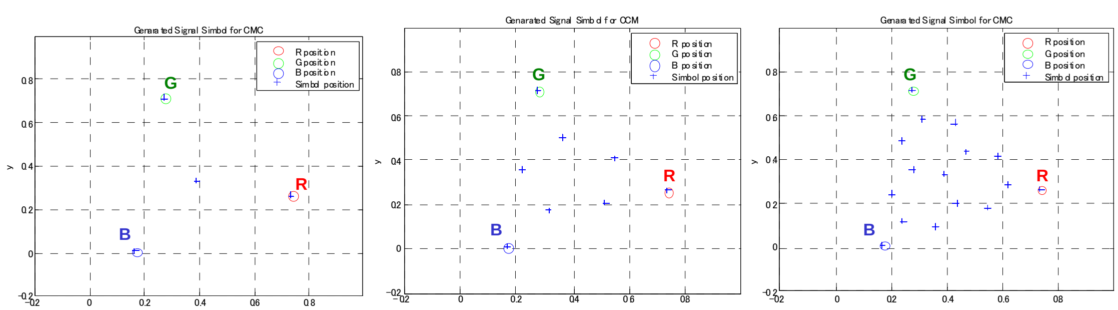
In CSK the raw bit rate is decided by the symbol rate and the number of color points in the constellation. This means CSK bit rate is not entirely limited by the frequency response of the LEDs.

B.1 Color constellation for CSK

Figure 6 shows the proposed color constellation for the CSK.

4CSK can send 2bits per symbol. 8CSK can send 3bits per symbol. 16CSK can send 4bits per symbol.

Those color constellations were decided for having same and max distance from adjacent symbols.



4 CCM (2bits/Symbol) 8 CCM (3bits/Symbol) 16 CCM (4bits/Symbol)

Figure 20—Color constellations for CSK

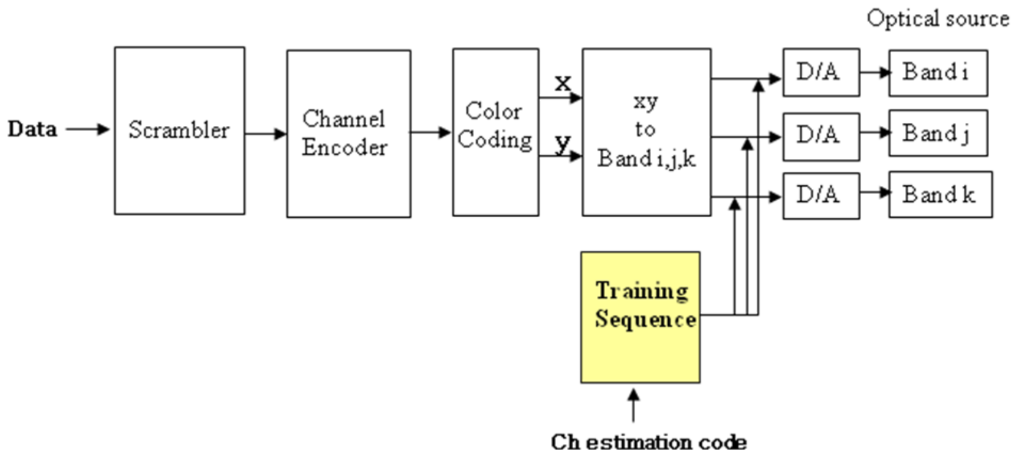


Figure 21—CSK system

Figure 21 shows the CSK system configuration, in case of 3 colors VLC system could have some degradationlight devices.

In that figure, transmit data is coded by the color coding block into xy values according to the xy color coordinates.

Figure 22 shows the CIE1931 xy color coordinate with the example for CSK symbol positions (constellation) in 4 point CSK (4CSK) case. In this case, 4 Symbol points are placed in the RGB tri angle. That means this system can send 2 bits data information per symbol.

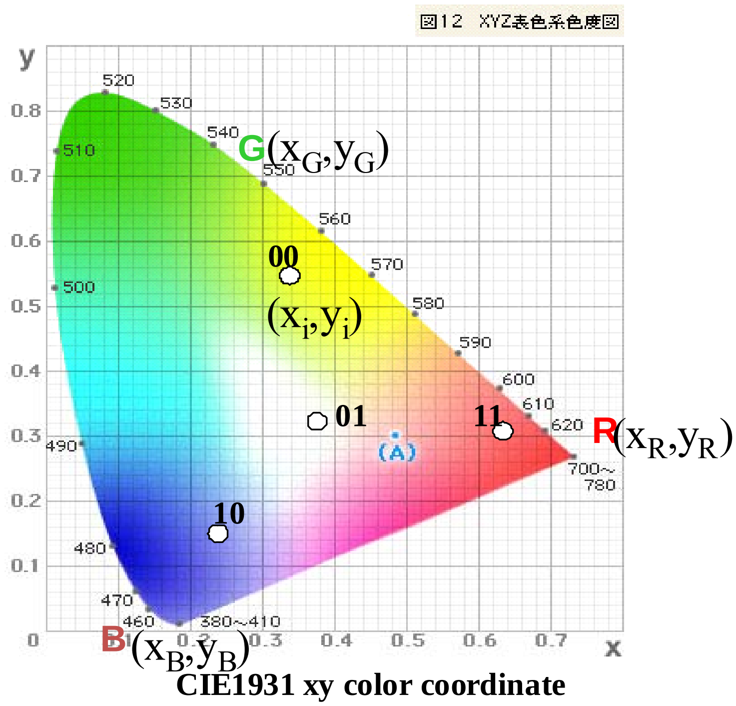


Figure 22—CIE 1931 xy color coordinate

All visible colors in the color palette defined by xy values. (xR,yR), (xG,yG), (xB,yB) shows the xy coordinates of the actual RGB LED devices. And (xi,yi) shows the one of the allocated color point in 4CSK.

The color point (xi,yi) is generated by 3 LEDs' intensity R, G and B in Figure 22. These xy values are transformed into RGB values.

The relation between (xR,yR), (xG,yG), (xB,yB) , (xi,yi) and RGB is showed by following simultaneous equations.

$$x_i = R \cdot x_R + G \cdot x_G + B \cdot x_B$$
$$y_i = R \cdot y_R + G \cdot y_G + B \cdot y_B$$
$$R + G + B = 1$$

In those equations, R, G and B show the normalized intensity of each LED.

In the receiver side, xy values are calculated from received RGB values. And xy values are decoded into the received data.

In this system, CSK symbols are provided as the visible colors which are made by RGB light sources.

And, the information is transmitted as the intensity ratio among RGB. Not as the each RGB absolute val-ues like WDM.

