Light-Fidelity and CSK Modulation

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1 Introduction

As the Internet of Things reaches its apex, by 2024 over 80 billion devices will be connected to the internet [1]. With this extent of connectivity and unprecedented communication, there are a series of questions to address. With the lack of sufficient frequencies in the Radio-Wave spectrum, do we have the means to support this extent of connectivity? How will global energy consumption deal with the exponential demand of new infrastructure (i.e. base stations)?

A possible solution to these questions comes in the form of a Visible Light Communication called Li-Fi, which uses off-the-shelf LEDs to transmit data. Li-Fi works by encoding data into subtle changes in the intensity of the light source. On the receiving end, photo detectors process the incoming intensities and convert the light signals into digital signals for consumption [8].

It presents numerous advantages: firstly, it is a green technology, meaning that it utilizes existing light infrastructure for wireless communications. This also comes with the benefit of drastically improving cost of installation and of energy consumption. Secondly, it addresses the so-called 'Wireless Spectrum crunch'[1] by using the Visible Light Spectrum, which is 10,000 times as vast as the Radio-Waves Spectrum, and completely unlicensed. Lastly, it has the potential to be deployed in areas such as aircrafts, hospitals, and nuclear power plants, which are sensitive to electromagnetic interference, as well as applications in underwater communications, vehicle-to-vehicle communications and the Internet of Things [4, 15, 7].

2 Modulation

In the paper "Modulation Techniques for Li-Fi", Professor Harald Haas and Mohamed Sufyan Islim state that "Li-Fi systems should be [..] considered as an illumination system with communications capability, and not the reverse". For this reason, there are various challenges that Li-Fi Modulation techniques encounter: controlling illumination, providing dimming capabilities and avoiding flickering are important factors that must be addressed by these schemes [7].

While there are currently over 30 modulation techniques for Visible Light Communications (VLC), this report will cover Colour-shift Keying, an interesting modulation scheme due to its unique properties and the fact that it is entirely specific to Li-Fi.

Color-shift Keying (CSK) is a modulation technique which transmits data by varying the colours emitted by the red, green and blue components of RGB LEDs. Although the relative intensities of the individual colours change over time, the overall intensity is always constant, and therefore this scheme introduces no perceivable flickering to the human eye [6]. Different combinations of these relative intensities are mapped to sequences of bits, therefore allowing encoding and decoding of data through light [7].

2.1 CIE XYZ 1931

CSK modulation is based on a widely adopted model for colour perception called the CIE XYZ 1931 colour space (Figure 1). CIE 1931 is a mathematical generalization of colour vision which allows us to define and numerically reproduce colours perceived by the human eye [3, 2].

For simplicity the model uses a two-dimensional space, dropping the third dimension of *intensity* and only representing the chromaticity (or colour, independent of brightness) of a given colour. Light red and dark red for example are considered to differ only in brightness, and would therefore share the same chromaticity value in this model. This allows any colour to be represented by two coordinates [x, y] [2], called a chromaticity dimension. The curved edge of the diagram is called the 'spectral locus', and represents the wave lengths of visible light waves, along with their corresponding values in nanometres [3].

[1] Lack of sufficient frequency bands in the Electromagnetic Spectrum to support the rapid growth of consumer devices
[2] The values of x and y are normalizations of X, Y, Z, which map to perceived red, green, and blue primary wave lengths.

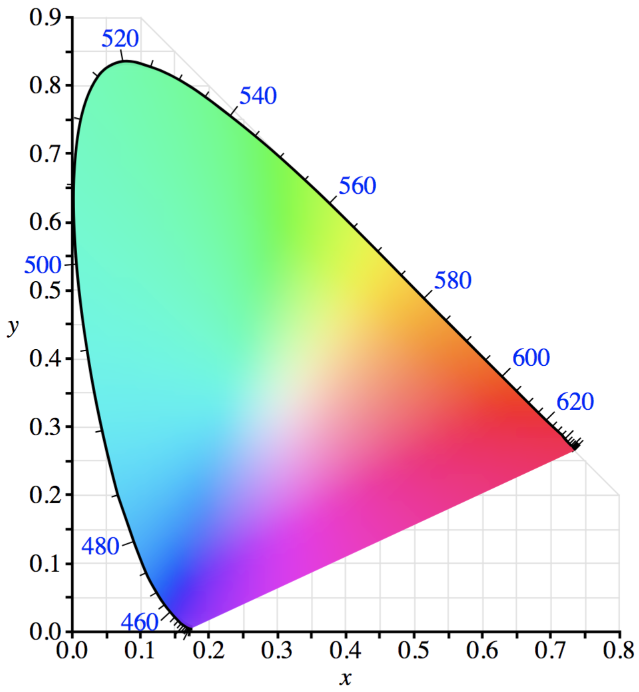

Figure 1: CIE XYZ 1931 Colour Space

To allow for multiple LED colour choices, the IEEE 802.15.7 standard divides the CIE 1931 spectrum up into 7 possible colour bands that can be used for communication. Each colour band has a unique code and is mapped to a specific [x, y] chromaticity coordinate in the colour space (Table 1, Figure 2) [5].

Table 1: Valid Colour Bands

Band (nm)	**Code**	**Center (nm)**	**[x, y]**
380-478	000	429	[0.169, 0.007]
478-540	001	509	[0.011, 0.733]
540-588	010	564	[0.402, 0.597]
588-633	011	611	[0.669, 0.331]
633-679	100	656	[0.729, 0.271]
679-726	101	703	[0.734, 0.265]
726-780	110	753	[0.741, 0.268]

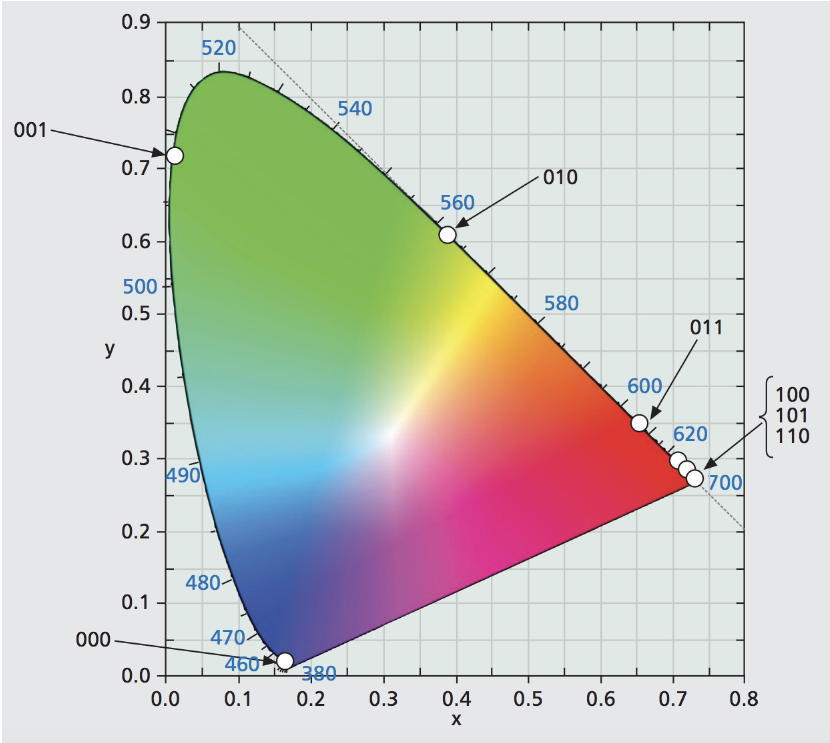

Figure 2: CIE 1931 with Colour bands

2.2 CSK Modulation

In Tri-LED (TLED) CSK exactly three different colour light sources must be used to generate a single CSK signal. These light sources form the vertices of the constellation diagram triangle. In theory, any mixture of colours within this constellation triangle can be used to represent data bits in CSK [14].

Currently there are 3 constellations defined by the IEEE 802.15.7 standard: 4-CSK, 8-CSK and 16-CSK. As stated before, each constellation takes on the form of a triangle within the CIE 1931 colour space. The three vertices of the triangle correspond to the central wavelengths (see Table 1) of the three different coloured LEDs [13].

Table 2 shows the possible colour band combinations that can be used to make up the vertices of a CSK constellation.

Table 2: Colour Band Combinations

	Band i	**Band j**	**Band k**
1	110	010	000
2	110	001	000
3	101	010	000
4	101	001	000
5	100	010	000
6	100	001	000
7	011	010	000
8	011	001	000
9	010	001	000

Each symbol within the constellation triangle represents a specific sequence of bits, and is mapped on to a specific [x, y] coordinate. This allows the sequence of bits to be reproduced using the colour defined by that [x, y] coordinate [13].

4-CSK can represent up to 4 symbols, each of which are 2 bits long: 00, 01, 10 and 11. In 8-CSK, a total of 8 symbols can be represented, which are each mapped to 3-bit long sequences: 000, 001, 010, 011, 100, 101, 110, Finally 16-CSK allows 16 symbols to be represented in the triangle, and each of these 16 symbols are assigned a 4-bit sequence.

2.3 4-CSK Constellation

4-CSK can transmit 2 bits per symbol which allows 2^2 (4) representations. Figure 3 shows the design of a 4-CSK constellation and its data mapping. In the illustration, the points I, J and K are the colour bands (the wavelengths) of the three light sources. S1, S2 and S3 are three CSK symbols which can carry 2 bits of information each (00, 10, 11, in this case) and coincide with the vertices of the triangle. The last symbol, S0, which represents the bit sequence 01, is the central constellation point [5, 12, 11].

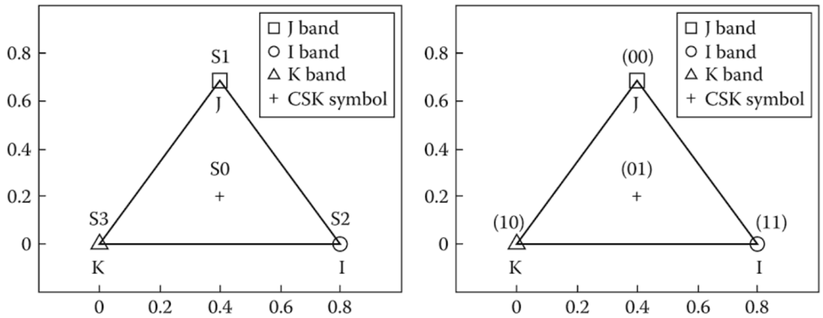

Figure 3: 4-CSK Constellation

2.4 8-CSK Constellation

8-CSK allows 3 bits to be sent per symbol, giving a total of 2^3 (8) representations. Once again, the vertices of the triangle I, J and K correspond to the central wavelengths of the light sources. Symbols S0-S7 are the coordinates of 8 colours, each assigned a different 3-bit combination [5, 11].

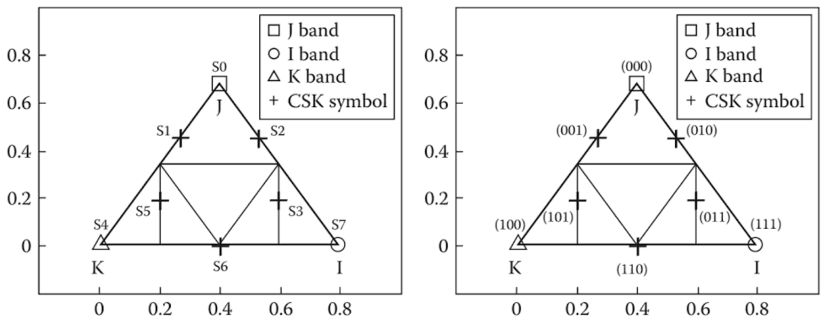

Figure 4: 8-CSK Constellation

2.5 16-CSK Constellation

16-CSK allows 4 bits to be sent per symbol, giving a total of 2^4 (32) representations. Once again, the vertices of the triangle I, J and K correspond to the centre wavelengths of the light sources. Symbols S0-S7 are the coordinates of 8 colours, each assigned a different 3-bit combination [5, 11].

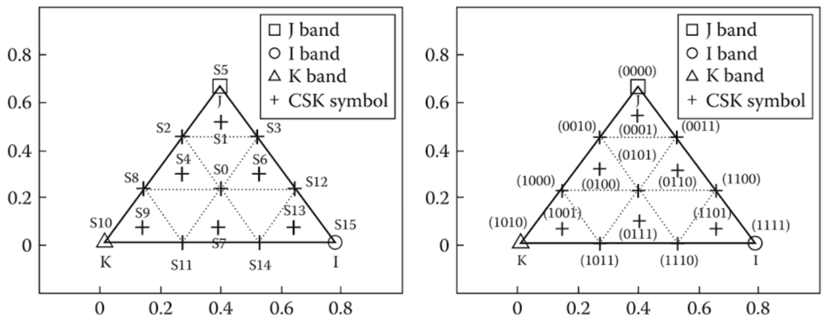

Figure 5: 16-CSK Constellation

2.6 CSK Block diagram

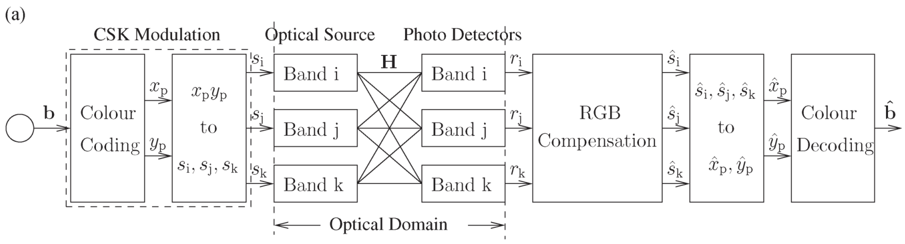

Figure 6: CSK Block Diagram [9]

The block diagram in Figure 6 illustrates the entire process of CSK modulation.

In this system, binary data at the transmitter is mapped onto a chromaticity dimension [x, y] using the constellation diagrams shown above. These chromaticities are then transformed into their corresponding intensities, R, G and B, using the equations:

$$x = P_i x_i + P_j x_j + P_k x_k$$

$$y = P_i y_i + P_j y_j + P_k y_k$$

$$P_i + P_j + P_k = 1$$

Where

$$[x_i, y_i], [x_j, y_j], [x_k, j_k]$$

are the chromaticity values at the central wavelengths of the three light sources (see Table 1) [10, 14].

On the other end, photo detectors detect incoming light intensity and perform the inverse process to decode the R, G and B intensities back into data bits, via the CIE colour coordinates [14, 8].

2.7 4-CSK Example

In this example, the three LED light sources chosen correspond to the bands 110, 010 and 000 (red, green and blue). Their corresponding [x, y] coordinates are shown in Table 1 and Table 4. The 4-CSK model allows 2 bits to be transmitted at a time. The four possible bit sequences are mapped to four different colours in the triangle. Their [x, y] coordinates are shown in Table 5 [5].

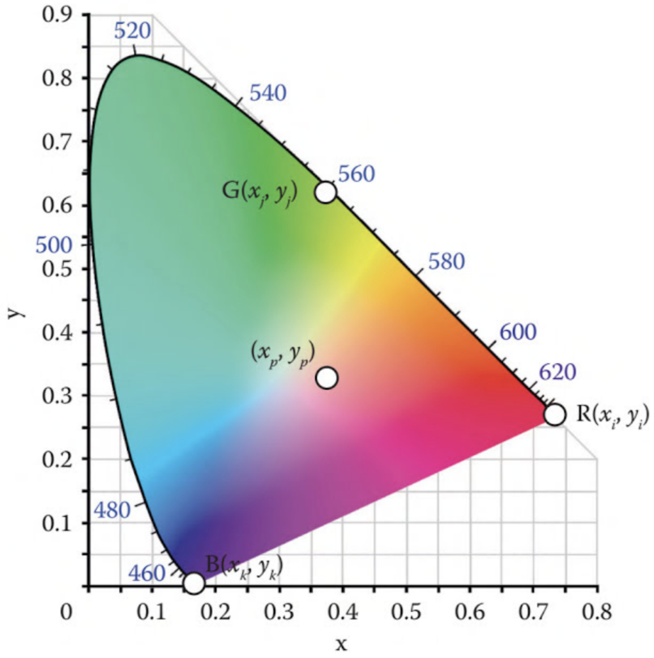

Figure 7: 4-CSK Example [11]

Table 3: 4-CSK Example

Table 4: Colour band coordinates

Band code	**[x, y]**
110	[0.730, 0.270]
010	[0.190, 0.780]
000	[0.180, 0.010]

Table 5: CSK symbol coordinates

Bit seq.	**[x, y]**
00	[0.190, 0.780]
01	[0.367, 0.353]
10	[0.180, 0.010]
11	[0.730, 0.270]

3 Conclusion

As stated previously, Li-Fi is a unique technology in that it uses an every day commodity, light, to provide communications capability. It deals with extremely practical issues, such as the negative impact that cooling down more and more cellular masts would have on global energy consumption rates as the number of devices connected to the internet *exponentially* increases. Li-Fi also offers intrinsic security measures, given that light is unable to traverse walls; this would make securing communications a straightforward task. If Li-Fi is used in conjunction with Wi-Fi, and not as its replacement, the future of global communications has the potential to be radically improved.

References

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