2.1 Introduction

From Shannon's initial work in information theory, it is clear that the capacity of a wireless link (and, by extension, of a network) is directly proportional to the available bandwidth. On the one hand, the system capacity in previous generations of cellular networks was diminished by limiting the spatial reuse of frequencies in an attempt to minimize interference. On the other hand, the most recent generation of wireless technologies, Long-Term Evolution (LTE) and beyond, rely on full frequency reuse along with advanced interference management algorithms to maximize the system capacity, i.e., each cell may use the entire available bandwidth. Nonetheless, despite employing interference management, there is a trade-off between bandwidth use and link connectivity [1].

Future networks are moving towards more heterogeneous architectures where multiple access points (APs) (e.g., macro-, pico-, femto-cells, relays and/or remote radio heads) are available in each cell. This will lead to an even denser spatial reuse of resources. These heterogeneous networks (HetNets) provide enhanced coverage in standard cellular networks, and improve the capacity of the system. Unfortunately, the increased frequency reuse introduces both inter- and intra-cell interference, which limits the achievable capacity of the network. To this extent, the conventional methods for capacity-improvement, i.e., enhanced spatial reuse and inter-cell interference coordination (ICIC), will be unable to support the growing demand for mobile communications. Therefore, a new, RF-orthogonal communication medium is required to fill the ever increasing capacity gap [1].

Visible light communication (VLC) has been identified as well equipped to provide additional bandwidth and system capacity, without aggregating the interference in the mobile network. VLC uses the visible light spectrum to transmit information; it can provide illumination and communication simultaneously by way of light emitting diodes (LEDs).

2.2 Historical Background

In the early 1800s, the US military used a wireless solar telegraph called "Heliograph" that signals using Morse code flashes of sunlight reflected by a mirror. The flashes are produced by momentarily pivoting the mirror, or by interrupting the beam with a shutter. The navy often uses blinking lights, i.e. Aldis lamps, to send messages also using Morse code from one ship to another. In 1880, the first example of VLC technology was demonstrated by Alexander Graham Bell with his "photophone" that used sunlight reflected off a vibrating mirror and a selenium photo cell to send voice on a light beam [2].

Until the late 1960s, radio and radar communications were more successful than optical communications (OC). OC started to get real attention with the invention of the light amplification by stimulated emission of radiation (laser) and the laser diode (LD) in the 1960s, followed in the 1970s by the development of low-loss optical fibres (OFs) as a medium for transmitting information using light, the invention of the OF amplifier in the 1980s, and the invention of the in-fibre Bragg grating in the 1990s. These inventions formed the basis for the telecommunications revolution of the late 20th century and provided the infrastructure for the Internet. The Nobel Prize in physics 2009 went to three scientists (Charles K. Kao, Willard S. Boyle, George E. Smith) who have played important roles in shaping the modern information technology due to their groundbreaking achievements concerning the transmission of light in fibers for optical communication. Advancements in basic opto-electronic devices, such as LEDs and LDs, p-intrinsic-n (PIN) photodiodes (PDs) and avalanche photo-diodes (APDs) and various optical components have attracted engineers to consider optical sources for wireless data transmission which has led to modern optical wireless communications (OWC) [3].

The first indoor OWC system was developed over 25 years ago. In 1979, an indoor OWC system was presented by Gfeller and Bapst. In their system, diffuse optical radiation in the near-IR region was utilized to interconnect a cluster of terminals located in a room to a common cluster controller. During the last ten years, the emergences of VLC fuelled by solid-state lighting (SSL) technology have been witnessed. SSL refers to a type of lighting that uses semiconductor LEDs as a source of illumination rather than electrical filaments (used in incandescent halogen light bulbs) or plasma (used in uorescent lamps). It is a promising technology to improve the energy efficiency of general illumination. SSL is a rapidly developing area, both in terms of commercial exploitation, and academic and industrial research. LEDs with a wide range of colors are available, including white light. The output power as well as device efficiencies are increasing rapidly. The field of applications is also expanding. White LEDs are commonly used as replacements for incandescent lamps due to more than 10 times improved energy efficiency. Therefore, LED lighting is set to revolutionize the way we illuminate our homes, offices, public buildings and streets .These SSL sources, being semiconductor devices, come with an additional feature. Their light intensity can be varied at very high speeds, and so their functionality can be extended by means of intensity modulation (IM) to also become a wireless communication device. VLC originated in Japan and the visible light communications consortium (VLCC) was established in November 2003. The VLCC has major companies in Japan on board and aims at publicizing and standardizing VLC technology. The formation of the VLCC has stimulated worldwide interest in VLC technology, and the first IEEE standard for VLC - IEEE 802.15.7 – has emerged recently. University of Edinburgh academics have worked on VLC since 2004 and have developed enhanced modulation schemes that enable high data rates to be achieved using standard LED light bulbs [2].

2.3Literature review:

In [7] the authors analyzed the performance of an indoor OFDM-OWC system in presence of LED clipping distortions. Two indoor OWC OFDM techniques were considered, an ACO-OFDM and DC-OFDM. The performance of these systems, in terms of average electrical OFDM signal power versus BER, DC power consumption, and considering a practical LED model, were studied. The result clearly highlight that LED clipping has significant impact on the performance of these systems and system design should consider optimizing the OFDM signal power, DC bias point, and LED dynamic range.

In [2] the authors present a theoretical and simulation results for the performance of ACO-OFDM and DCO-OFDM in AWGN for intensity-modulated direct-detection systems. Constellations from 4 QAM to 1024 QAM are considered. For DCO-OFDM, the optimum bias depends on the constellation size which limits its performance in adaptive systems.

In [19] the author’s analyses the nonlinear clipping distortion of ACO-OFDM based VLC and proposes an optimal power allocation method for reducing the clipping distortion. Firstly, the LED nonlinear clipping distortion based on the clipping process model that original signal directly added nonlinear clipping distortion components was analyzed. Then, the effective signal to noise ratio (ESNR) was defined to measure the clipping distortion, and the clipping distortion analysis was converted into ESNR analysis. Finally, the optimal power allocation under optical power constraints base on the principle of ESNR optimum was proposed. Simulation results show that reasonable power allocation can effectively reduce the LED nonlinear clipping distortion and ensure that the bit error rate (BER) is less than 10-3.

2.4Comparison of VLC with Other Communication Technologies

2.4.1 VLC versus Radio Waves

Radiofrequency communications is the most popular technology today, it also has disadvantages. VLC is compared with radiofrequency using five main concepts [4];

Capacity: Radio spectrum is full and it is difficult to find radio capacity to support the demand of wireless data transmissions for media applications. The radio waves are limited, expensive and there is only a certain range of it. By using VLC more spectrums will be available and due to the infrastructure of LED-based lights installed in the world there is a potential for VLC as transmitters.

Efficiency: Radio waves consume a lot of energy while VLC is highly energy efficient since illumination and transmission of data are done at the same time.

Cost: VLC transmitters and receivers devices are cheap. There is no need for using expensive RF units.

Safety: Radio wave creates Electromagnetic Interference (EMI), known to interfere with airplanes' instruments and equipment in hospitals, and is potentially dangerous in hazardous operations, such as power/nuclear generation or oil and gas drilling. On the other hand, VLC uses light instead of radio waves, which is intrinsically safe and does not create EMI. Hence, this technology can be used in many places.

Security: Radio waves penetrate through walls and they can be intercepted. By using VLC data is transmitted where the light is because light does not penetrate through walls, that is to say, VLC provide a secure data communication.

Human Health: The transmission power of radio waves van cannot be increased over a certain level because there are serious health risks for humans. VLC is an attractive candidate in a consumer communication system.

2.4.2 VLC versus Infrared Communication

Infrared Technology is a safe and widely used technology. The differences between VLC and infrared communication are summarized in the following points [4];

Data Rate: Infrared Communication sends data at a rate of 20Mb/s while VLC can send data up to 100Mb/s.

Distance: The transmission distance for VLC is possible up to several meters due to its illumination requirement. Since the infrared communication is used for a remote controller, the maximum distance is ~ 3 meters.

Noise Source: Due to the wavelength of the light source, the noise sources will be different. For infrared communication, noise comes from ambient light containing infrared light. In the case of VLC, the sunlight and other illumination light can be noise sources.

Services: Infrared Technology is used in communication only while VLC is used both for illumination and communication.

Application: Infrared Technology is used in remote control and point-to-point connection while VLC can be used in many applications such as; underwater communications and defense and security services.

2.5 VLC for Indoor Communication

VLC channel modeling significantly depends on environment. For this reason, channel modeling for VLC for three main environments based on possible application areas reviewed as: indoor, outdoor and underwater.

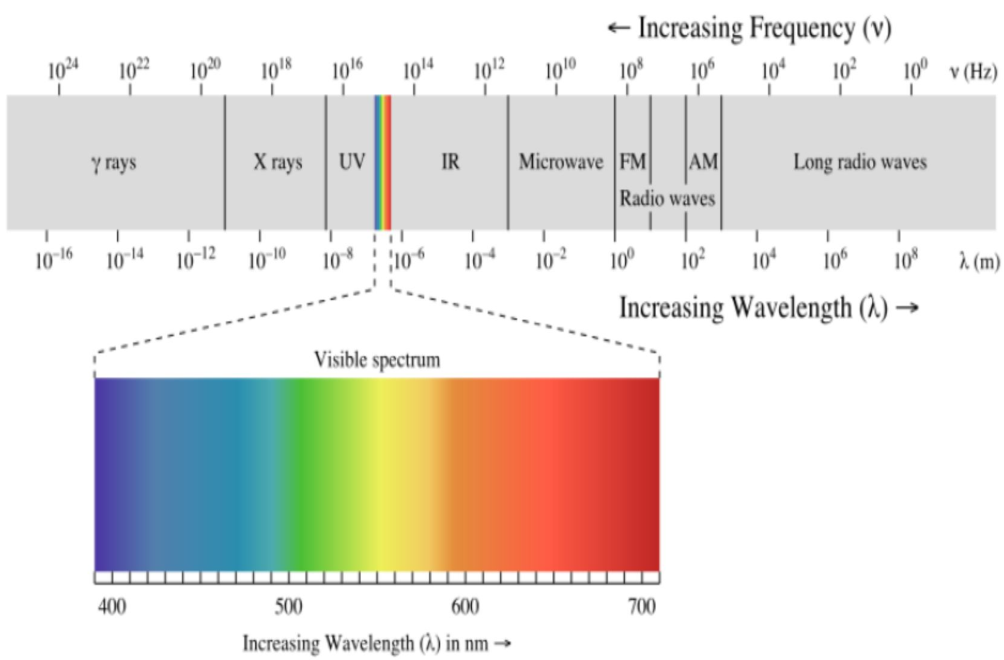

Figure 2.1: The visible spectrum [5].

VLC relies on the visible light (VL) spectrum between 375 nm and 780 nm for communication, rather than the cluttered, scarce and expensive RF spectra used today for wireless communications. In fact, VL is not regulated, and can therefore be used freely for communication purposes, significantly reducing the costs for operators. Thus, VLC presents a viable alternative to traditional communication methods and may be used as a complement to current RF communications [5].

2. 6 VLC Applications

The applications of VLC are not restricted to indoor uses. Some main applications of VLC are detailed in the following [5]

Hazardous environments:

Visible light communications is an attractive choice for areas where there is a risk of explosions (such as mines, petro-chemical plants, oil rigs etc.) as it provides both safe illumination and communications.

Vehicle and transportation:

White LEDs can also be used in the automotive field to communicate audio or digital data between cars, between traffic infrastructure and cars, between robots or even between aircraft. Figure 2.2 displays visible light communication between head and tail lights of two cars.

Figure 2.2: Car-to-car visible light communication between head and tail lights [5]

Location based services:

There exist some applications for VLC that enable estimation of user location. The geospatial information authority (GSI) in Japan has already started the activity of indoor location estimation using white LEDs.

Defense and security services:

Visible light is a strong candidate for new defense and security systems. The fact that visible light cannot be detected on the other side of a wall has considerable security advantages.

Aviation:

Light emitting diodes are already used in aircraft for illumination and can also be employed to provide media services to passengers. Such application reduces the aircraft cost and weight since there is no need of wires.

Figure 2.3: VLC in an aircraft cabin [4]

Hospitals and healthcare:

Visible light is well-suited for communication in hospitals and healthcare, especially around MRI scanners and in operating theatres where RF radiations are undesirable.

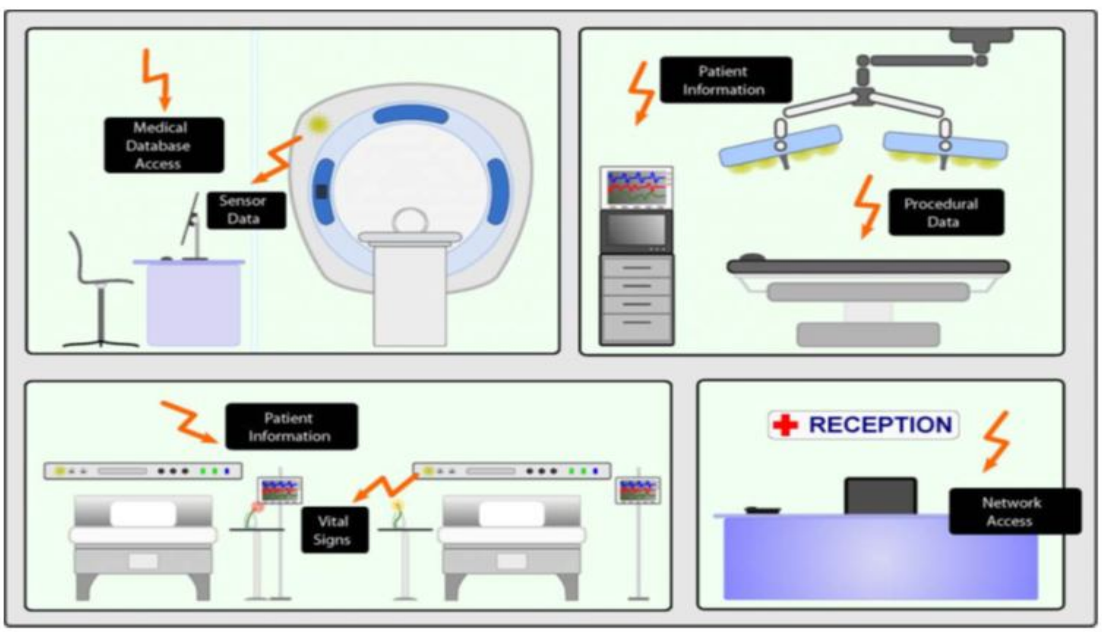

Figure 2.4: Medical equipment sensitive to radio wakes can work with VLC[9]

Underwater communications:

Visible light is very attractive for environments where radio waves do not propagate for a long distance. Since radio waves do not travel well through thick electrical conductors like water, VLC can be used as an alternative to support underwater communications. Such advancement can enable underwater vehicles and divers to communicate to each other.

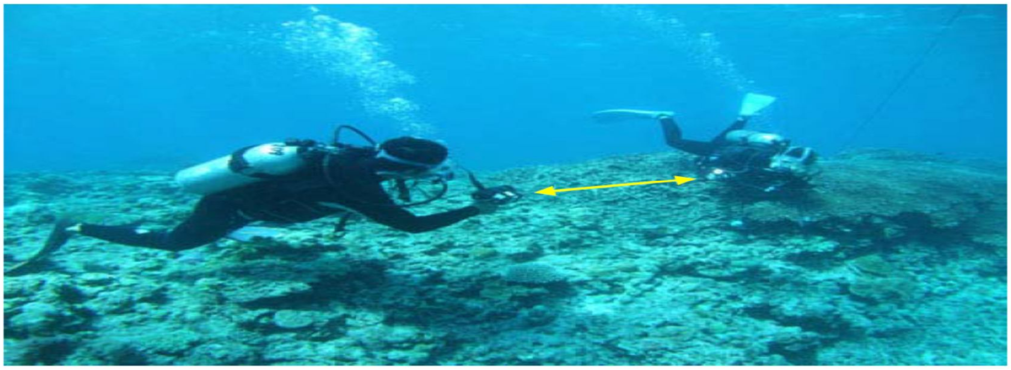

Figure 2.5: VLC in underwater communications [4]

2.7 Basic VLC System structure

Figure 2.7 shows the basic structure of VLC system

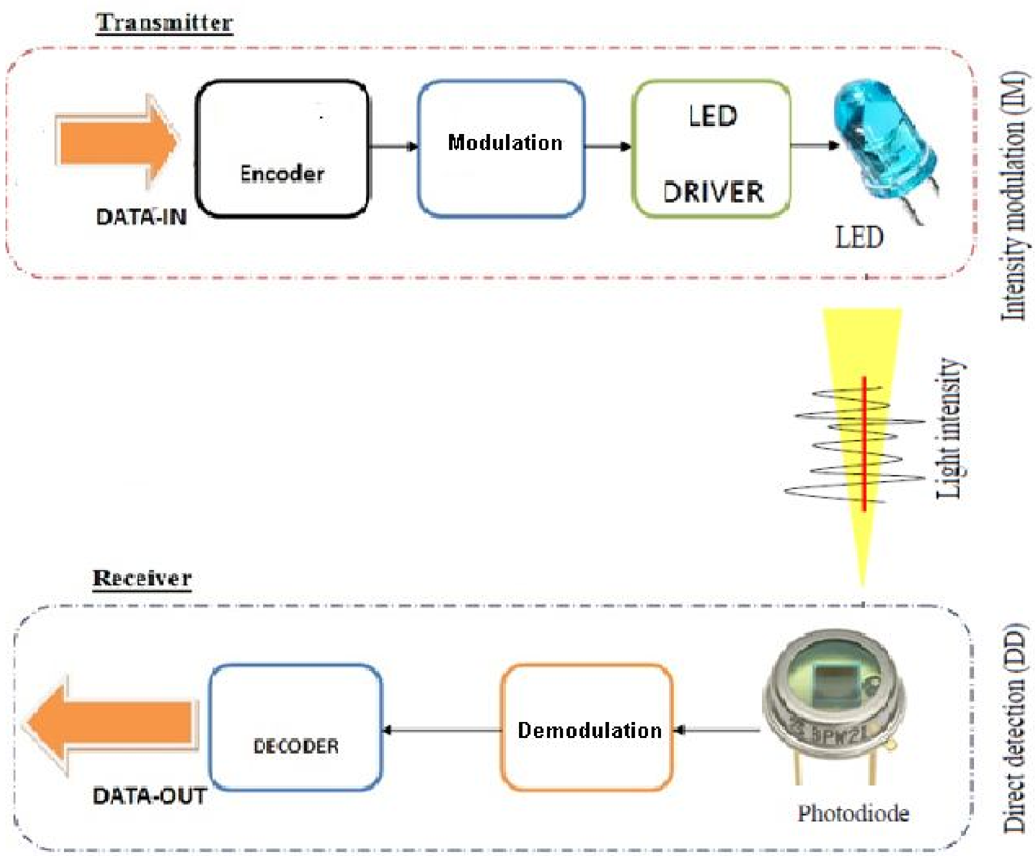

Figure 2.6: The basic structure of VLC system

2.7.1 Intensity Modulation and Direct Detection

In RF wireless communications, the baseband signals are up-converted to a designated RF carrier, and sent to the air via antennas at transmitter. Receiver employs one or more antennas, each followed by a down-converter, which includes a local oscillator and a mixer, to generate baseband signals.

In VLC, the baseband signals are up-converted to optical carriers at the transmitter, and the receiver down-convert optical signal into baseband electric signal. The electric-optic and optic-electric conversions do not rely on expensive oscillators and mixers, but only low-cost LEDs and photodiodes. The most feasible up-conversion scheme is intensity modulation (IM), in which the desired waveform is modulated onto the instantaneous power of the optical carrier. The most practical down-conversion is direct detection (DD), where a photodiode produces a current proportional to the optical intensity.

In IM/DD, only magnitude information, but no phase, can be modulated. The basic concept of intensity modulation and direct detection is that the received signal is the instantaneous current in the receiving photodetector, which is proportional to the integral over the photodetector surface of the total instantaneous optical power at each location [1].

2.7.2 White LEDs

At the transmitter, the light emitting diodes (LEDs) convert the amplitude of the electrical signal to the intensity of the optical signal. VLC relies on white LEDs which already provide illumination and are quickly becoming the dominant lighting source to transmit data. VLC modulate white LEDs at high rates in a way that is imperceptible to humans [7].

Generally, white LEDs used in VLC technology are classified into two types, namely trichromatic and blue-chip LEDs. Trichromatic LEDs are fabricated by mixing light of the three primary colors (red, green, and blue) obtained using three different LED chips (spectrum shown in Figure 2.7(a)). This type is mainly used for architectural design purposes and is more expensive compared to blue-chip LEDs. Blue-chip LEDs have a phosphor layer on top of a single blue chip and they are typically found in most white LED bulbs available in the market (spectrum shown in Figure 2.7(b)) [8].

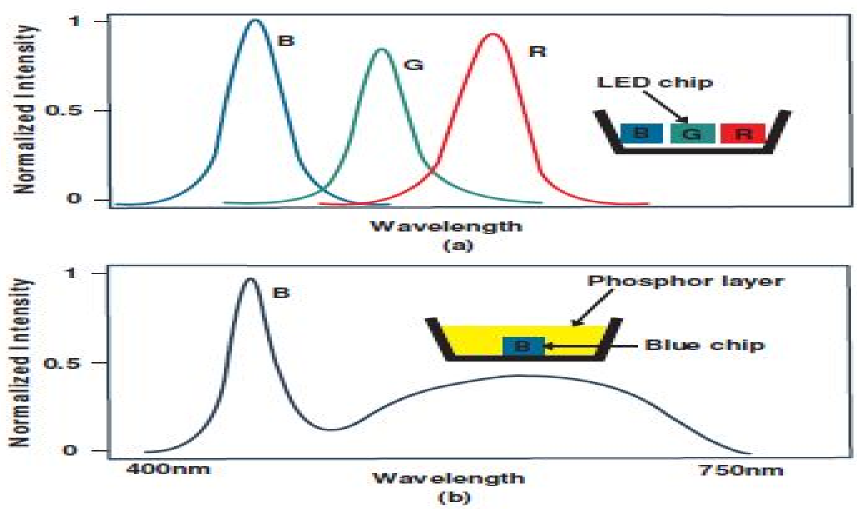

Figure 2.7: (a) Trichromatic white LEDs, (b) Single-chip white LEDs. The trichromatic LED has peaks for red, green, and blue. The blue-chip LED has a dominant peak and a lower wider peak from 500 nm to 600 nm [8].

2.7.3 Photodiodes

Photodiodes are solid-state devices that are used to perform the optical to electrical conversion. They produce an output electrical current, proportional to the received intensity signal. The received current is then processed to extract the transmitted information [8].

2.7.4 VLC Modulation Techniques

There are a number of different methods that can be used to modulate the data over the visible light spectrum; the main methods are;

On-off keying (OOK)

As the name suggests the data is conveyed by turning the LED off and on. In its simplest form a digital ‘1’ is represented by the light ‘on’ state and a digital ‘0’ is represented by the light ‘off’ state. The beauty of this method is that it is really simple to generate and decode. However, this method is not optimal in terms of illumination control and data throughput

Pulse Width Modulation (PWM)

This method conveys information encoded into the duration of pulses. More than one bit of data can be conveyed within each pulse, but they may have to be longer pulses than for OOK, so there is no great advantage with this scheme. It is also possible to transmit data in an analogue format using this scheme which is also relatively simple to implement.

Pulse Position Modulation (PPM)

For PPM the data is encoded using the position of the pulse within a frame. Again more than one bit can be transmitted in each pulse, however the duration of the frame must be longer than for a single OOK bit, so again it is not necessarily more efficient. It does have the advantage of containing the same amount of optical energy within each frame

Spatial Modulation (SM)

There are a number of techniques that allow one to determine the source of an optical signal. If one can determine its source one can either use the multiple sources of information to convey multiple stream of independent data (one from each source), or one can use the source of the signal as part of the information encoding itself. The multiple sources could be multiple LEDs within a single fixture.

Color Shift Keying (CSK)

This can be used if the illumination system uses RGB type LEDs. By combining the different colors of light, the output data can be carried by the color itself and so the intensity of the output can be constant. The disadvantage of this system is the complexity of both the transmitter and receiver [4].

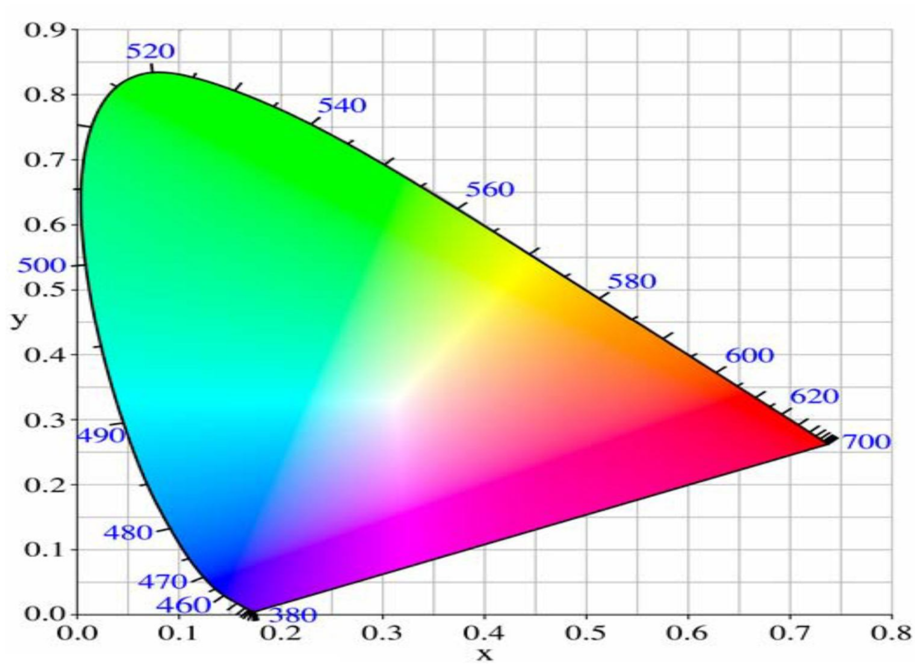

Figure 2.5 Chromacity diagram for CSK[9]

Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a kind of multicarrier modulation that has been incorporated in many wireless standards due to its several advantages including: robustness against frequency-selective fading channels, simple one-tap equalization, easy digital modulator/demodulator implementation and high spectral efficiency. It uses orthogonal subcarriers, which overlap in the frequency domain.The basic idea of OFDM is to divide a high-speed digital signal into several slower signals and transmit each slower signal in a separate frequency band. The slow signals are frequency multiplexed to create one waveform.If there are enough slow narrowband signals, the symbol duration in each one is long enough to essentially eliminate inter-symbol interference [5].

OFDM signals are in general bipolar signals and have both negative and positive amplitudes. Since VLC uses IM, a real and unipolar valued signal needs to be produced. Therefore, the conventional OFDM scheme used in RF communications should be modified. To achieve a real valued output signal, Hermitian symmetry is used on the parallel data streams into the IFFT input. This comes at the cost of losing half the available bandwidth [6].

The resulting real signal becomes bipolar, but it should be unipolar. For this purpose, direct current biased optical OFDM (DCO-OFDM) utilizes addition of direct current (DC)-bias to the bipolar signal to convert it to a unipolar signal. DCO-OFDM consists in adding a DC bias to the real valued signal and hard clipping the remaining negative values. The data symbols are assigned to all odd and even subcarriers. The data rate of DCO-OFDM system is given by,

$$R_{\{DCO\}} = \left(\frac{N/2-1}{N+N_g}\right) B \log_2 M \text{ bits/s.} \tag{2.1}$$

where

B is the channel bandwidth, N_g is the number of guard subcarriers

M is the size of the considered constellation diagram.

This means that a maximum of (N/2) − 1 subcarriers out of N subcarriers can be used to carry useful data. The DCO-OFDM has ((N/2) – 1) independent complex inputs and the bipolar time domain signal is used to modulate a DC biased LED. This DC bias which is carrying no information results in optical power efficiency penalty, mainly in IR transmission. However, in VLC, a DC bias point is required for illumination and may not cause severe power efficiency loss. The DC bias value depends on the LED characteristics and can significantly affect system performance. Moreover, the hard clipping results in a significant clipping noise, especially for low bias levels and large constellation sizes [12].

Another technique to avoid the DC bias is asymmetrically clipped optical OFDM (ACO-OFDM) which utilizes the properties of OFDM without requiring DC-biasing. In order to create a symmetric time domain signal, only the odd sub-carriers are used in ACO-OFDM. In this way, negative values in signals are set to zero without altering carried information. Half of the spectrum is wasted in ACO-OFDM. For this reason, DCO-OFDM generally provides better spectral efficiency at the expense of power compared to ACO-OFDM [8].

ACO-OFDM was proposed as an optical power efficient alternative of DCO-OFDM. In ACO-OFDM, only the odd subcarriers are modulated. Therefore, the achieved data rate for ACO-OFDM systems is given by,

$$R_{\{ACO\}} = \left(\frac{N/4 - 1}{N+N_g}\right) B \log_2 M \text{ bits/s} \tag{2.2}$$

where

B is the channel bandwidth, N_g is the number of guard subcarriers

M is the size of the considered constellation diagram.

ACO-OFDM uses only half of the sub-carriers used by the DCO-OFDM to carry data, which results in an anti-symmetric time-domain signal. The obtained bipolar signal is then made positive by clipping the entire negative excursion. Since only the positive part is transmitted, ACO-

OFDM has more optical power efficiency than DCO-OFDM [12].ACO-OFDM systems have several advantages as follows,

• A DC bias is avoided which can be considered as an extra power consumption.

• Larger amplitude of the signal can be considered which covers the full dynamic range of the LED.

Conversely, ACO-OFDM systems suffer from several drawbacks as follows,

• ACO-OFDM systems sacrifice a large portion of the data rate to achieve the asymmetrical property.

• For VLC systems, a DC bias is needed for lighting purposes which makes the clipping at the zero level ineffectual [11].