# Modulation Techniques for Visible Light Communication using White LEDs in 5G Network

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## Abstract

The recent interest in short range indoor optical wireless communication using white LED has been developed by the widespread deployment of solid-state LED lighting in household and business places. In this work two important modulation techniques used namely, colour shift keying (CSK) and asymmetrically clipped optical (ACO-) OFDM in visible light communication (VLC) is highlighted. The error rate performances of different modulation schemes are compared and it is found that ACO-OFDM outperforms CSK by 15 dB SNR at $10^{-6}$ symbol error rate.

## 1. Introduction

The fifth generation (5G) cellular network is being deployed. 5G combines heterogeneous networks originated from device to device (D2D), massive MIMO, machine to machine (M2M), mmWave as well as optical wireless communication (OWC). The point is 5G should not be a mere evolution of 4G. There is a dramatic increase in the number of subscribers using mobile broadband systems every year. Powerful smartphones and laptops are populating the markets capable of providing advanced broadband multimedia services. Currently cellular frequencies below 6 GHz have been used heavily. One of the critical upcoming challenges will be the scarcity of radio frequency (RF) spectra allocated for cellular communications. Moreover, most of the cellular calls originate from indoors typically 80% of time. Indoor users communicating with the outdoor base station, the signals have to penetrate room walls which significantly drops the data rate and spectral and energy efficiency of wireless transmissions deteriorates. Energy efficient indoor wireless communications can contribute to the worldwide reduction of $CO_2$ emissions.

At microwave frequencies the spectrum is scarce, but it is found plentiful in the millimeter wave (mmWave) and optical domain. Moreover, spectrum is made unregulated in mmWave and optical wireless communication and thereby it provides a promising solution to overcome the RF spectrum crisis. mmWave technologies have already been standardized for short-range services (IEEE 802.11ad) and small-cell backhaul. With tremendous advancement in white LED technology, the IEEE form a standardization 802.15.7 for high-data-rate visible light communication (VLC) using white LEDS. VLC uses wavelengths in the band 380 –780 nm and employs white light emitting diodes (LEDs) as signal transmitters and PIN photodiodes or avalanche photo-diodes as signal receivers. Data rates of 3.5 Gb/s have been reported from a single LED transmission. Very recently Samsung has introduced features of both photo detectors (PD) and CMOS integrated in a Mobile/Android to detect light in the mobile [1]. Using existing lighting fixtures in the ceiling of a room personal optical wireless networks can be established. Several optical base stations

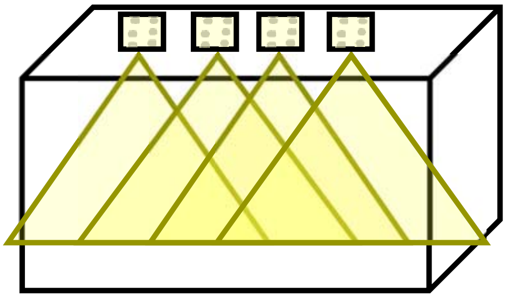

Fig.1. Indoor optical attocells for VLC

by LED arrays produces optical wireless network of very small cells within a room. The small cell architecture using VLC is shown in Fig.1. Each cell may cover an area of 10 square meters designated as optical attocells in analogy to femtocells in RF indoor communications. White LEDs have the potential for luminous efficiencies exceeding 300 lm/W which is quite higher than incandescent lamp of 100 lm/W. Advantages of white LED as signal transmitter are solid state device with long life, high tolerance to humidity, high off-on switching speed and energy efficient lighting. Two types of white LEDs are available. (a) Single-chip and (b) Trichromatic. The emission spectrum of the first one consists of the blue emission from single chip LED traverses phosphorescence material of longer wavelength. The resulting emission color is white with a bluish tint. However, on-off switching speed is slow as phosphorescence is a slow process. On the other hand, Trichromatic three LEDs red-green-blue (RGB) mount on a single cover exploits mixing of three primary colours to produce white light. Switching speed is higher and therefore, RGB LEDs are ideal for high-speed data modulation. White light producing RGB LEDs can be used to provide room illumination as well as high-speed data access.

In this work, we have mainly focused on CSK and OFDM modulation. Not enough work has been done on CSK modulation and there is a scope for further research in this domain to improve its data-rate performance. Finally, we will compare its bit error rate performance with OFDM as well as with other types of modulation techniques used in OWC.

## 2. Modulation Techniques

There are several techniques for modulating the information-data onto the optical carrier of LEDs. In optical wireless communication, the information is carried by the intensity of the light. Therefore, the information carrying signal should be real valued. In contrast digital modulation schemes for RF communication use complex valued signals. So optical wireless signals need some modifications to make data real valued. The various modulation schemes in VLC used by various researcher are on-off keying (OOK), pulse position modulation (PPM), Orthogonal Frequency Division Multiplexing (OFDM), Color Shift Keying (CSK). As mentioned earlier Color Shift Keying modulation has been standardized by IEEE 802.15.7 in visible light communication. However direct detection (DD) on-off keying has been used by many researchers because of its simplicity. However, OOK modulation is spectral efficient but not power efficient. PWM signal is used as data modulation for its power efficiency and assist dimming control in VLC. But its spectral efficiency is lower. Currently, multicarrier OFDM is envisaged as upcoming modulation technique in VLC because of its advantage of high spectral efficiency and boosting data rate. Another advantage is that this modulation format is compatible with 4G and 5G cellular communications.

### 2.1. CSK based Modulation:

The CSK standard fixes seven colours bands (shown by 000 to 111) [2] whose wavelengths lie between 380nm to 700nm. They are defined in the periphery of the colour space as shown in Fig.1. X and Y are the chromaticity values and it forms chromaticity coordinates for different light sources. Three R, G and B colour bands are chosen from seven colours such that their vertex points are corresponding to the red, green and blue tri-chromatic LEDs selected as signal transmitters. These vertices are joined to form a chromaticity triangle as shown by three dotted lines in Fig.2. To have better decoding performance at the receiver the area of the triangle for the given R, G and B chromaticity vertices should be as large as possible. Let the chromaticity coordinates of the vertices of the triangle be denoted by $(x_R, y_R)$ for red, $(x_G, y_G)$ for green and $(x_B, y_B)$ for blue in the periphery of the colour bands namely, (101), (010), and (000)

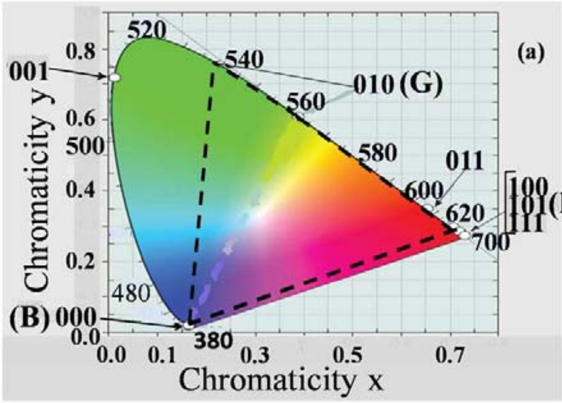


Fig.2: LED colour mapping into chromaticity values

respectively. These colour bands are chosen because commercial LEDs are available in these wavelengths. Symbol constellations in the X, Y chromaticity plane for 4-levels, 8-levels and 16-levels CSK are shown by crosses in Fig.3. Those are formed using triangle median rules [2, 3]. From the chromaticity values of the transmitted symbols the LED powers corresponding to red, green and blue can be calculated using Eq. (1).

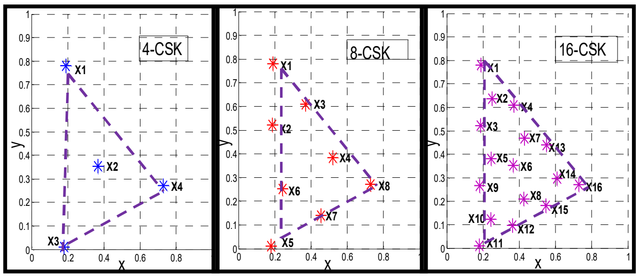


Fig.3. *Formation of 4-CSK, 8- CSK and 16- CSK constellations in the chromaticity triangle in Fig.2.*

$$x_n = (x_R L_{Rn} + x_G L_{Gn} + x_B L_{Bn}) / (L_{Rn} + L_{Gn} + L_{Bn})$$

$$y_n = (y_R L_{Rn} + y_G L_{Gn} + y_B L_{Bn}) / (L_{Rn} + L_{Gn} + L_{Bn}) \quad (1)$$

In equation (1) the $L$`s represents the LED powers which are weighted by eye sensitivity factors [4]. Combining the powers of three LEDs, *M*-different combinations of white light is possible to produce for *M*-level CSK. Knowing R, G and B coordinates of three corners of the chromaticity triangle, chromaticity coordinate $(x_n, y_n)$ for the rest *(N-3)* constellation points within the triangle can be found [5]. The incoming data symbols are mapped into the chromaticity values and those are fed to R, G and B LEDs for transmission. In this work we have assumed linear current versus power characteristics of white LEDs. In the receiver symbol are to be decoded from LED current produced at the photo diode output. We have used Voronoi decoding algorithm [5] to determine constellations within chromaticity triangle. Decoded CSK symbols are shown in Fig.4. We have assumed only additive white Gaussian noise power is introduced at various stages namely, in the channel and transimpedance

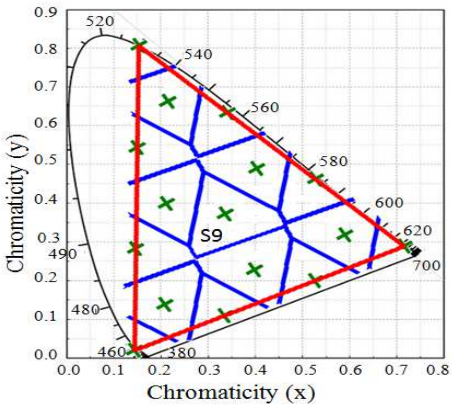


Fig4. Voronoi segmentation algorithm for decoding *16*-level CSK

amplifier after the PD during the detection process. The performance of decoding worsens as noise power is increased in the channel which introduce symbol error rate.

### 2.2 On-Off Keying (OOK) and Pulse Position based Modulation (PPM)

OOK symbols are generated by altering the 'ON' and 'OFF' levels as shown in Fig.5. It is easy to alter dimming by i) varying On and OFF levels of the OOK signal or ii) changing ON and OFF period of the waveform by inserting compensation time into the modulation waveform by means of a time multiplexing scheme. The first method might cause chromaticity shifts due to the LEDs being under- driven current, but it gives a constant bit rate and second method has lowered the achievable bit rate as the light is dimmed.

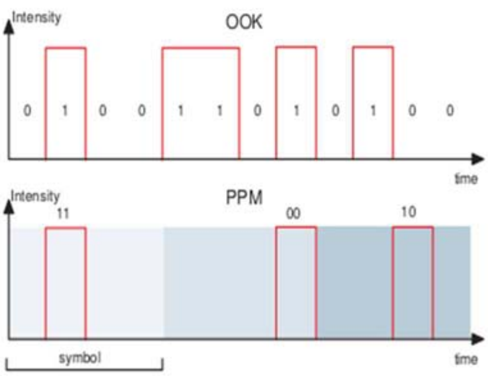


Fig.5 OOK and PPM modulation

In the PPM modulation technique, the symbol time is partitioned into equal slots of time as shown in Fig.5. In one of the slots, the pulse position is used to recognize the transmitted pulse. This modulation technique suffers from low spectral efficiency as well as low data rate. PPM expands the signal bandwidth compared to OOK, but provides higher power efficiency. But PPM imposes more system complexity as both slot and symbol-level synchronizations are required at the receiver.

### 2.3 Optical OFDM Modulation using Intensity Modulations

Optical OFDM is well investigated by Jean Armstrong [6]. In typical (non-optical) OFDM systems, the information signal can have both positive and negative values. (bipolar) and complex. In contrast in a typical intensity modulated optical system, the information is carried by the intensity of the optical signal and therefore can only be positive (unipolar) and real. A real baseband signal OFDM signal can be generated by constraining input data vector to have Hermitian symmetry. OFDM has a disadvantage of having large peak to average power (PAPR). Large PAPR drives LED output power to nonlinearity which leads to distortion. In order to mitigate this in this work asymmetrically clipped OFDM (ACO-OFDM) [7] is considered. In ACO-OFDM the bipolar OFDM signal is clipped at the zero level: all negative going signals are removed. If only the odd frequency OFDM subcarriers are non-zero at the IFFT input, all of the clipping noise falls on the even subcarriers, and the data carrying odd subcarriers are not impaired. ACO-OFDM generation is shown in the Fig.6. Here input QAM input symbols are Hermitian mapped which are mapped to odd subcarriers. Only odd subcarriers are modulated with symbol information. Even subcarriers 0, 2, 4… are not modulated. Then IFFT is carried out and cyclic prefix (CP) is added to generate ACO-OFDM symbol.

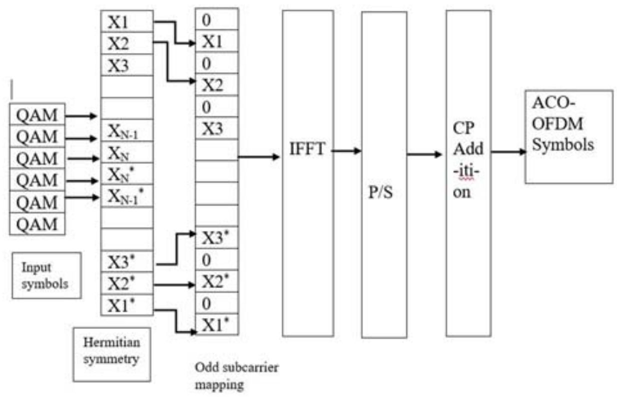


Fig.6: Generation of real and positive OFDM signal using ACO-OFDM

Table 1 summaries closed form expression for bit error rate (BER) and bandwidth requirement for different modulation types as ready reference. *P* is the transmitted power, $N_0$ is the noise power spectral density, $R_B$ is the data rate. BER expression for OOK is straightforward to derive. Expression for PPM is obtained from [8] and expression for CSK is derived by us assuming that CSK signal can be constructed from *N*-level PAM for each R, G or B signal levels and from this combined probability of error for a symbol in CSK is derived. Close form expression for OFDM can be found from [9].

**Table-1:** BER for different modulation schemes

| Modulation scheme | BER for a particular optical power $P$ | Bandwidth requirement |
|---|---|---|
| OOK | $Q\left(\frac{P}{\sqrt{N_0 R_B}}\right)$ | $R_B$ |
| L-PPM | $Q\left(\frac{P}{(1/\sqrt{0.5L}\, log_2 L)\sqrt{N_0 R_B}}\right)$ | $LR_B/log_2 L$ |
| CSK | $\left[1-\left(1-\frac{1}{N}\sum_{n=1}^{N}\sum_{k=1}^{N} Q\left(\frac{\sqrt{P}\lvert k-n\rvert}{2^{R_B/k}\sqrt{2N_0}}\right)\right)^3\right] log_2 N$ | $3R_B/log_2 N$ |
| OFDM | $p_e=\frac{1}{N_D}\sum_{k=1}^{N_D}\left(\frac{2\sqrt{M}-1}{\sqrt{M}\log_2 M} erfc\left(\sqrt{\frac{3SNDR(k)}{2(M-1)}}\right)\right)$ | $R_B/log_2 M$ |

## 3. Simulation results

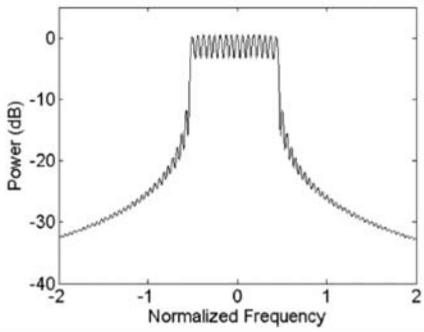


Fig.7: ACO-OFDM spectrum

Monte-Carlo simulation is performed to decode CSK symbols which are shown in Fig.4.in subsection 2.1. OFDM Symbol decoding is just the reverse process shown in Fig.6. Monte-Carlo simulation is performed to find bit/symbol error rate for ACO-OFDM for different received SNR. ACO-OFDM spectrum is shown in Fig.7. No offset DC bias needed in the LEDs. So OFDM dynamic range is increased. As found from the analysis as well as from Fig.7 ACO-OFDM spectra contains less clipping noise and shoulder of OFDM spectra is lowered which mitigates inter-channel interference. Plots for BER for other kind of modulation used in VLC is shown in Fig.8 for comparison purpose.

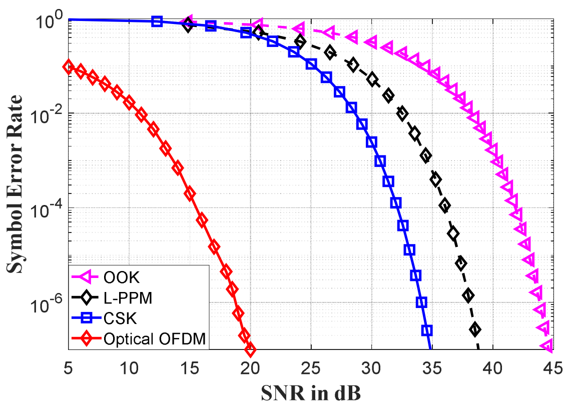


Fig.8 Comparison of SER with SNR for different modulation used in VLC

It is found that OFDM outperforms other modulation used in VLC in terms of error rate. At 10-6 BER, 15 dB SNR improvement is found in ACO-OFDM compared to CSK modulation.

## 4. Conclusions

We have explained different kinds of modulation used in VLC and their pros and cons are discussed. It is found that CSK and OFDM are the two important modulation techniques. Monte Carlo simulation is carried out and symbol error rate for ACO-OFDM is found quite less compared to CSK modulation at a given SNR. In order to achieve $10^{-6}$ symbol error rate ACO-OFDM requires 15 dB less SNR than CSK. However, there is a scope for further investigation of CSK modulation to improve its performance.

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