Development of a visible light communication system for reducing flicker in low data rate requirement

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Abstract: In visible light communication, the illumination as well as transmission of data is done using the same light source. In this paper, the problem of flicker is dealt with and an experimental setup is developed using frequency shift keying (FSK) that is much more efficient than the commonly used on-off keying (OOK). A flicker free transmission is obtained which is 62% lower than OOK. A decrease of BER by 86.8% and 85.3% compared to the later is obtained at a distance of 30 cm and 480 cm respectively. For FSK, a 10% increase in BER is found at an angle of 3° which shows considerable improvement over OOK, as the later showed the same error only at 1° (measured at 100 cm). The experimental arrangement is described in detail that would enable replication of the setup in low bit rate requirements.

Keywords: visible light communication; VLC; photodiode; frequency shift keying; FSK; light emitting diode; LED; on-off keying; OOK.

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1 Introduction

In the 21st century, wireless communication has become an inevitable part of human life round the globe. The radio frequency (RF)-based systems are already developed to cope with the basic demand. However, the fast growing home networks has caused bandwidth shortage in the electromagnetic (EM) spectrum (Khan, 2017). The RF-based communication is also restricted in critical situations such as in hospitals, airplanes, petrochemical plants, etc. (Ding et al., 2015). As such, researchers are in pursuit to find an alternate reliable mode of communication system that is also safe in such environments. This has lead to the development of optical wireless communication (OWC) that may provide huge spectrum relief and is harmless in critical environments. At present, two types of OWC are possible: the visible light communication (VLC) and infrared (IR) communication using a frequency range from 430–770 THz and 300 GHz–430 Thz respectively. In terms of frequency range, visible light has almost ten thousand times more bandwidth compared to RF (Khan, 2017). The demand of VLC has become popular in the scientific community after the discovery of blue light emitting diode (LED), from which white LED can be made. White LEDs is also consistently replacing the already available illumination source such as compact fluorescent lamp or halogen bulb (Chatterjee et al., 2018; Falcitelli and Pagano, 2016; Li at al., 2014). The demand is progressively increasing due to its inherent property of low cost, energy efficient, environmentally safe, long lifetime, etc. (Lee at al., 2012; Okuda et al., 2014). Apart from this, semiconductor LED can be switched at a very high speed for the human eye to detect, and can be used as a transmitter of digital information. The restriction within the room is an added advantage for secure mode of communication (Siddiqui et al., 2015; Tanaka et al., 2001). At present, there are two standards of VLC namely the visible light communication consortium (VLCC) in Japan and IEEE. The former, publish the Japan Electronics and Information Technology (JEITA) (Falcitelli and Pagano, 2016). The latter introduces both medium access control (MAC) and physical layer (PHY) air interface which supporting peer to peer and star configuration. The data rates supported in PHY layers are from 11.67–96 Mbps.

Though VLC offers an alternate mode of communication, the challenges faced is many, like the multipath effect, shadowing, background light, dimming and flicker. Multipath effect is the phenomenon in which signal reach the photo detector after reflection from walls in addition to the line of sight (LOS). The impulse response of LOS is usually short and sharp while that of the non-line of sight (NLOS) is broad, depending on the reflectivity of the walls and the size of the room. This broad response causes inter symbol interference and decrease the speed of data transmission (Hosseinianfar et al., 2017). Shadowing is the blocking of the direct path to the photo detector caused by static or moving objects; later leading to time varying channel. In shadowed situation, the impulse response of the channel has only the NLOS component from which data is retrieved. Background light is the presence of external light sources or sunlight in the field of view (FOV) of the photo detector even in the presence of background light.

Illumination levels of VLC should be strong enough so that, the signal to noise ratio (SNR) is quite high even in the presence of background light. VLC modulation should also enable dimming at any bit rates. Dimming (Suriza et al., 2017) is an important feature of indoor lighting system through which illumination level can be controlled using suitable modulation. Flicker is another problem in VLC. This is the fluctuation of illumination level perceived by the human eye < 200 Hz) (Rajagopal et al., 2012) at low bit rates. The IEEE 802.15.7 standard recommends, the human biological effect of flicker below this frequency must be avoided (Rajagopal et al., 2012). Continuous exposure of flicker is injurious to eyes and damage eyesight.

Flicker originates mainly due to two reasons. Firstly, due to low data rates and secondly due to long runs of 1's or 0's in the digital signal transmitted. Many applications require transmission at low bit rates, especially for slowly varying parameters like temperature, humidity or even bio-medical signals. The latter is required in hospital monitoring where the use of RF is restricted. Sensor data for health monitoring are slowly varying signal (for example, blood pressure, non-invasive: 60 Hz; blood pressure, invasive: 50 Hz; pulmonary artery pressure: 50 Hz, central venous pressure: 50 Hz; ECG: 250 Hz; photoplethsymography: 30 Hz; cardiac output: 20 Hz and body temperature: 0.1 Hz) and as such low data rates would suffice for accurate monitoring (Dimitriou and Ioannis, 2008; Paksuniemi et al., 2005). It must be noted that cellular phones, WCDMA, PHS handsets, WLANs and RFID systems are found to cause serious concern on the working of the nearby medical equipments; especially those that are indispensable for critical care like ventilators, infusion pumps, ECG monitors, anaesthesia machines and blood pressure monitors (Paksuniemi et al., 2005; Periyasam and Dhanasekaran, 2013). VLC can be an option in such situations. VLC can also be used in smart homes (Cahyadi et al., 2015; Tan et al., 2013) providing healthcare facilities for elderly people in the comfort of their homes.

A successful flicker mitigation scheme should be able to transfer data as low as 10 bps without causing any health hazard. Many methods are presented in papers to reduce flicker. However, all these papers are mainly confined to simulation only and hardware implementation is not available. Moreover, these papers have not presented the many variability of implementation like distance of coverage, angle and errors associated with transmission. A practical implementation is also missing that makes it hard for any implementer to design an associated hardware. In this paper, a VLC modem is developed to remove low frequency flicker with the help of frequency shift keying (FSK) modulation scheme. The system enables transmission at data rates as low as 60bps in a flicker free environment. The associated hardware is described in detail that would enable the implementation and duplication of the same. The dependency of the efficiency of the system with respect to variability is analysed in detail. The efficiency of this method is compared with on-off key (OOK) which is the commonly used method in VLC (Vanderka et al., 2015). Such a concept is given in Chatterjee and Tiru (2018) where the optimisation of the VLC setup is reported elaborately. The variability studied is bit error rate (BER) as a function of bit rate, minimum data rate for flicker and angle of coverage. The paper is sectioned as follows. Section 2 presents a literature review of the currently available methods to reduce flicker, their limitations and the importance of the current work. In Section 3, the components of typical VLC systems are optimised and variability analysed. These results form the basis of the FSK-VLC modem. Section 4 describes the experimental setup to reduce flicker in VLC. Section 5 is the analysis the results and then finally, Section 6 concludes with its key issues and future scope.

2 Literature review on flicker mitigation and importance of current work

Table 1 reviews the methods available to mitigate flicker. In Fang et al. (2017), polar code 'recursive encoding' structure is used to generate short runs of 1 s and 0 s for arbitrary code rate without the need of extra coding components. The results of the work shows that, for OOK-VLC at a dimming ratio of 25% and 75%, the coding gain of the proposed scheme is about 4.6 dB and 1.4 dB higher compared to Reed-Solmon (RS) and low density parity check coding respectively. However the disadvantage is that, it works at 400 kbps which is not suitable for mitigation of low frequency flicker. In Mejia et al. (2017) finite state machine (FSM) coding scheme is used to mitigate flicker. This is soft decision decodable using Viterbi algorithm which limits the number of consecutive 1 s and 0 s in the transmitted sequence. A flicker measurement is proposed which provides optical clock rate (OCR), modulation format and pulse shape of the transmitted signal. Using FSM, better flicker mitigation is achieved in a smaller number of states, however at the cost of capacity. The FSM-based code provides a trade-off between flicker and the system performance and a flicker free transmission is obtained till 200 bps. In Oh (2013), a pulse dual slope modulation (PDSM) scheme proposed by Anand and Mishra is used to remove flicker. When the transmitted bit rate is low or, for long runs of 1s and 0s this scheme shows better performance to mitigate flicker compared to pulse position modulation (PPM) and pulse width modulation (PWM) scheme. In Oh (2013), a hardware was implemented, but no information regarding data rate or angle is given. In Li et al. (2016), a redundant run length (RLL) limited encoding scheme is considered for data transmission, as well as for flicker mitigation. It uses two LEDs for asynchronous communication using OOK-VLC, which uses OFF periods for VLC reception. The result shows that a reliable communication at a bit rate of few kbps can be obtained at a distance of 10 cm using a single LED. In Li et al. (2016), the distance obtained is only 25 cm. Table 1 gives a comparison of the work done in this field.

Most of the work done in flicker, is based on simulation results only and very low frequency flicker was ignored (Cailean et al., 2014; Niaz and Kim, 2017). The distance covered is also very less (maximum 80 cm) and most of the papers have ignored the angular coverage and the actual design of the arrangement. Except (Mejia et al., 2017) the bit rates are very large of the order of kbps. The dependency on the variability like the associated electronics or the transmitter and receiver elements has also been ignored. This paper, described a hardware flicker mitigation scheme that is successful to reduce flicker to as low as 60 bps up to a distance of 480 cm through an angle of 20°. The variability is also analysed in detail that allows any researcher to reproduce the experimental setup with considerable accuracy.

Table 1 Comparison of other published work with this current work in terms of flicker mitigation

Approach	*Fang et al. (2017)*	*Mejia et al. (2017)*	*Oh (2013)*	*Li et al. (2016)*	*Niaz and Kim (2017)*	*Cailean et al. (2014)*	*This paper*
Type	Simulation	Simulation	Hardware	Simulation, hardware	Simulation	Simulation	Hardware
Method used	Forward error correction using polar code	Finite state machine coding	Pulse dual slope modulation	Redundant run length coding, multilevel dimming for data transmission	Fixed dimming OOK for VLC	Miller coding technique	FSK, OOK base VLC
Distance	Not available	Not available	Not available	5–25 cm	80cm	Not available	Up to 480 cm
Bit rate	400 kbps	200 bps	Not available	Few kbps	Not available	100 kbps	10–600 bps
Angle coverage	Not available	Not available	Not available	0°	30°	Not available	20°
Transmitter	LED	LED	Not available	R, G, B LED	LED	LED	LED
Receiver	Not available	PD	Not available	LED	PD	PD	PD

Table 2 Comparative analysis of Chatterjee and Tiru (2018)

Driver	*Solar cell*		*Photodiode*	
	Distance (cm)	*MBR (kbps)*	*Distance (cm)*	*MBR (kbps)*
AD1	50	54	50	970
	250	22	250	770
DD1	50	61	50	1,020
	300	18	300	775
DD2	50	70	50	1,100
	325	21	325	825
DD3	50	74	50	1,140
	350	22	350	855

3 Experimental setup for VLC and analysis of dependencies using OOK

A typical VLC setup consists of a transmitter and receiver constituting of suitable optoelectronic devices. The transmitter could be LED, and the receiver either a photodiode (PD) or a solar cell (SC). LED drivers are used to amplify the signal suitably before transmission. For an effective communication, the coupling between different components should be perfect to be used on a broader scale. In Chatterjee and Tiru (2018), the dependencies on components of a workable VLC system was done for efficient data transfer. The block diagram of the experimental setup for the analysis is shown in Figure 1. The information to be transmitted is a square wave which is suitably amplified by a driver before applying to a LED and received by the photo detector. The OOK transmission scheme is used here. Four types of drivers (AD1, DD1, DD2 and DD3) are tested as shown in Figure 2. AD1 is a transconductance amplifier which converts the input voltage into current that can be passed through the LED. DD1 is a series driver circuit, DD2 is a shunt driver circuit while DD3 is a combination of series and shunt driver circuit with additional capacitor and resistor. Here, the base capacitor improves the turn on and off characteristics of the transistor. The drivers are made of NPN BD139 transistor which has a maximum operating junction temperature of 150°C and a, maximum collector current of 1.5 A. The LED used is a yellow phosphor coated 1 watt blue LED, which produces white light. A biasing voltage of 3.8 V is supplied to the driver. The voltage drop across the base emitter junction of the transistor is 0.7 V, a drop of 3.03 V across the LED and a minimal drop done across the other components. A reflector of transmitting beam angle 20° is used at the surface of the LED to increase the directionality of the emitted light. In the receiver, a convex lens is used just before the photodetector to increase the intensity of the received signal. The photo detectors are either a PIN PD (BPW34) or SC (polycrystalline silicon) which adequately converts the optically transmitted signal into an electrical signal for amplification. The received signal from the photo detector is applied to a transimpedance amplifier (TIA) and a comparator before being observed by a digital storage oscilloscope (GWINSTEK GDS-1052-U, 50 MHz, 250 MS/s). A comparative analysis from Chatterjee and Tiru (2018) is shown in Table 2. It is seen that, for a fixed distance, with a PD as a receiver, at least 15 times higher bit rate is obtained compared to a SC. The performance of DD3 is best compared to other three. As such the combination of PD and driver DD3 is the best optimised combination for the VLC setup. Though the low data rate is the main focus of this paper, the DD3 driver is used so that in the later stage, the system can be optimised for both low and high bit rate requirements (Chatterjee and Tiru, 2018).

Figure 1 Block diagram of VLC setup

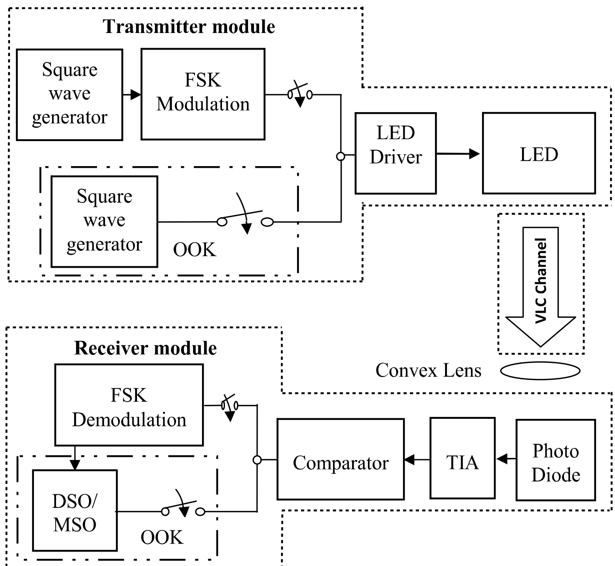
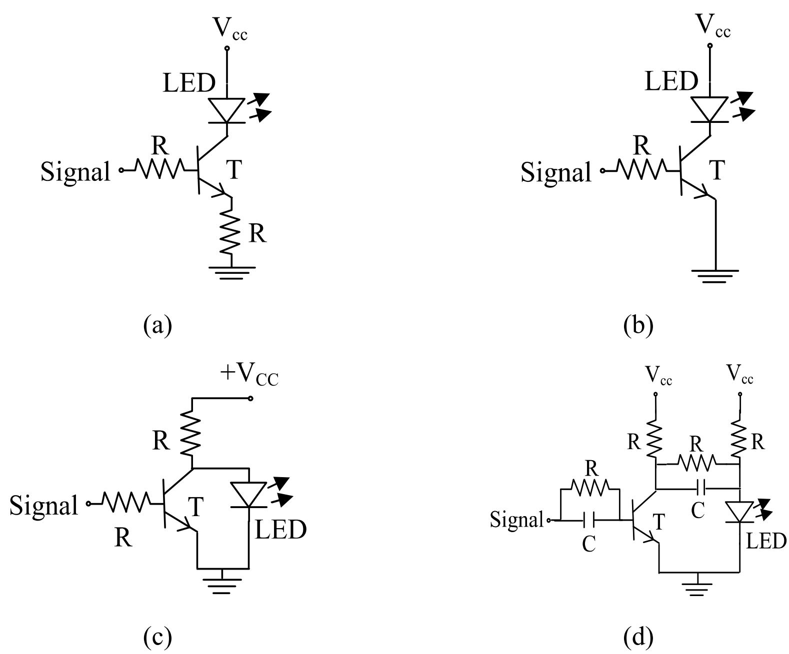


Figure 2 LED driver, (a) AD1 (b) DD1 (c) DD2 (d) DD3



4 Flicker mitigation scheme in VLC using FSK

The flicker mitigation scheme developed, uses the same experimental setup shown in Figure 1. However, the transmitter used is the FSK block instead of the OOK modulator and a FSK demodulator is used after the comparator. The description of the transmitter and receiver is as follows.

4.1 Transmitter module

The transmitter module includes the square wave generator (taken as the message signal), FSK modulator, LED driver and LED. The FSK modulator consists of an IC 555 used in the astable mode. The free running frequency (*f*) and the duty cycle (*DC*) of the astable multivibrator are given by equations (1) and (2) respectively (Gayakwad, 2012).

$$f = \frac{1.44}{(R_1 + 2R_2)C} \tag{1}$$

$$DC = \frac{R_1 + R_2}{(R_1 + 2R_2)} \times 100\% \tag{2}$$

The multivibrator is set with a free running frequency of 3.9 kHz (R_1 = 0.69 kΩ, R_2 = 1.5 kΩ, C = 0.1 μF) and a *DC* of 59%. The message signal from the signal generator is inserted in the pin 7 of the 555 IC and the FSK modulated signal is obtained at the pin 3. The mark and the space frequencies are taken to be 4.1 kHz and 3.7 kHz respectively. The FSK signal is now inserted on the input of driver DD3. The FSK signal causes intensity modulation of the LED and is sent through free space and received by the receiver module.

4.2 Receiver module

The receiver module consists of a PD, a TIA, comparator, FSK demodulator and a mixed signal oscilloscope (MSO, Keysight MSO X2024A). The TIA converts the low amplitude signal to a suitable level for the comparator using IC LF356. The operational amplifier has a slew rate of 12 V/μS. The coupling between the TIA and the comparator is done by using a capacitor which removes the direct current (dc) component of the voltage appearing at the receiver circuitry due to an external light source near the FOV. The comparator converts the output of the TIA into TTL which is actually a FSK modulated signal. The TTL signal is then allowed to pass through the FSK demodulator circuit and captured by the MSO. The FSK demodulator circuit consists of a phase locked loop (PLL, IC 565) which has a wide operating range from 0.1 Hz to 500 kHz. The PLL locks the output signal at pin 7 according to the input signal at pin 2. The DC voltage at pin 6 is changed according to the frequency of the input signal. The free running frequency or the centre frequency of the demodulator and the lock range is given by equations (3) and (4) respectively.

$$f_0 = \frac{0.3}{R_1 C_1} \tag{3}$$

$$f_{lock} = \frac{8 f_0}{V} \tag{4}$$

where V is the total supply voltage and the value of R_1 = 0.78 kΩ, C_1 = 0.1 μF and the centre frequency of 3.8 kHz with a lock range of 2 kHz is obtained. In the 565 IC, the frequency shift is obtained by an inbuilt voltage controlled oscillator whose output corresponds to the modulating signal. It works in such a manner, that it locks the input signal frequency and tracks it between the two possible frequencies with a DC shift at the output. Further, an RC filter and comparator LM741, is used to decode the transmitted square wave and thereby observed in the MSO.

5 Results and discussion

In order to check the efficiency of the system, the main variability analysed is the minimum bit rate at which flicker appears and the dependency of BER on distance and the angle. To compare with the OOK modulation, the same is also estimated using the experimental setup in Figure 1. The variation of BER with bit rate for various distances is shown in Figure 3. The BER is also found by varying the angle and is plotted as in Figure 4. The results of the readings are summarised in Table 3. The maximum distance is found to be 480 cm, because above which the intensity of light is insignificant to be detected. The salient features of the analysis are given as follows:

a *Minimum bit rate at which flicker disappears:* In FSK, a flicker free system could be obtained to as low as 60 bps which is nearly 62% lower than that for OOK. This is because, in FSK modulation, each high or low of the digital signal is represented by a high frequency mark or space frequency signal that causes the LED to switch at a much faster rate than the digital bit itself. This causes the flicker to disappear even at low bit rates. However, for OOK, the switching of the LED is at the bit rate itself.

b *Performance based on the BER:* For both the modulation, there is a minimum bit rate when the BER appears. The bit rate at which error occurs is nearly three times more in FSK than the OOK. It is seen that in all the graphs, the BER is higher in OOK compared to FSK below ~450–490bps. The reverse is true at higher bit rates above this range. The percentage improvement of BER in FSK is 86.8% compared to OOK at a transceiver distance of 50 cm which becomes 85.3% at a distance of 480 cm (computed at the minimum appearance of bit error in FSK). For higher bit rate, the significant increase in BER for FSK modulation is due to the use of lower space and mark frequency of 3.7 kHz and 4.1 kHz of 555 IC compared to what is necessary for successful detection.

c *BER and angle:* A comparison of BER with angle shows that BER for OOK is much higher compared to FSK as the angle from the direct LOS (or 0°) increases. The BER is estimated up to ±10° because beyond this, the intensity of light is very small and could not be received by the PD. For the BER to increase by 10% of what is obtained at 0°, the angle for OOK is only 1° which are much smaller than the 3° in FSK.

The reason behind the increase in BER with angle is that the procedure of detection depends on comparing transmit and receive signal using a XOR gate and D flip flop. If the inputs to the BER detector have the same frequency and *DC*, then there is no errors are detected. However, if the *DC* is changed at the received bits, then errors are detected. It is seen that even if the transmit square wave has a DC of ~50%, it is no longer so when the signal is received at an angle. Figure 5 gives the increase in DC as angle is increased from 0° to 10°. The increase in *DC* is found to be more in OOK than FSK. A change in the *DC* results in an increase of BER. For OOK, the BER directly connected to the increase in *DC* of the data signal. However, in FSK signal, though the *DC* of the mark and space frequencies changes in the detector, the demodulator detects the frequencies and gives correct regeneration of the bit stream. This causes the BER to be lesser in FSK than the OOK. FSK at 10° the *DC* of the received signal is 64%, which increases to 86% for OOK-based VLC.

Figure 3 Dependency of BER on bit rate for FSK and OOK modulation schemes at different distances between the transmitter and receiver (see online version for colours)

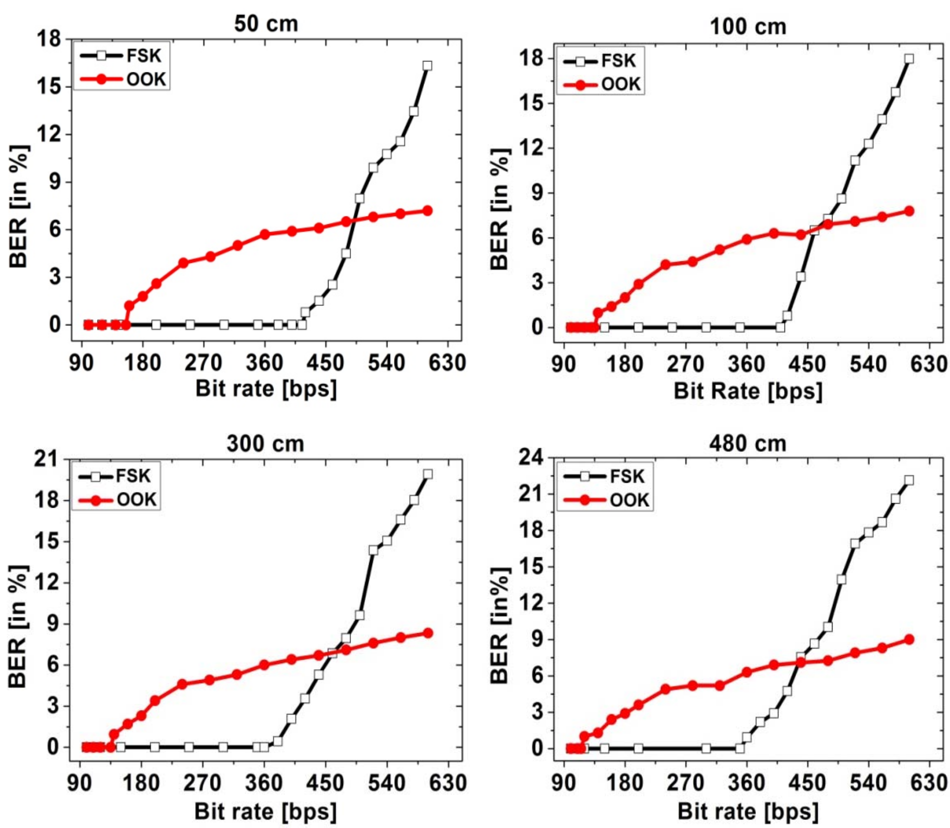


Figure 4 Dependency of BER on angle for FSK and OOK modulation schemes at a distance of 100 cm between the transmitter and receiver (see online version for colours)

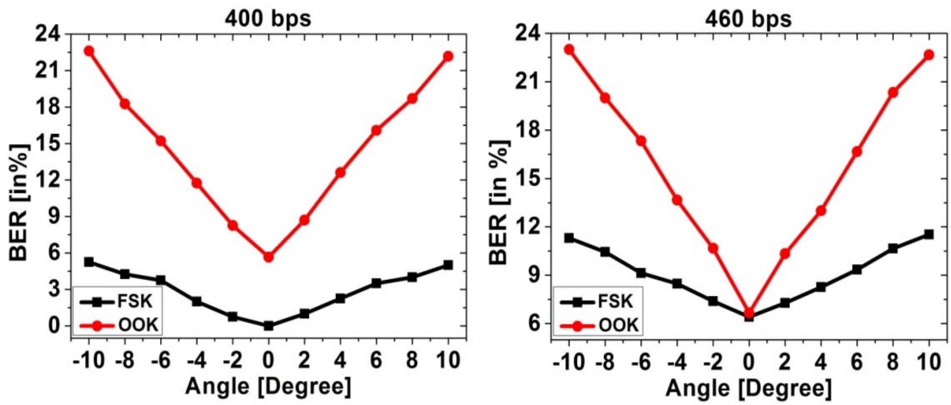


Figure 5 *DC* vs. angle for OOK and FSK modulation (see online version for colours)

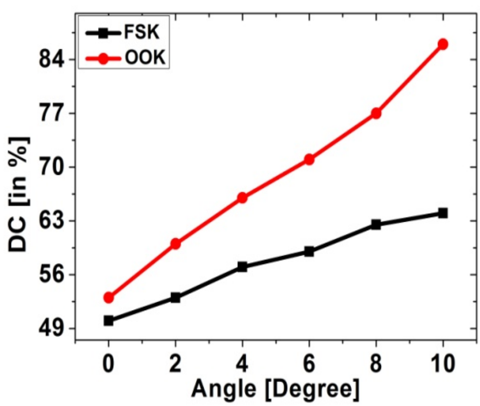


Table 3 Comparison of the performance of FSK and OOK modulated in a VLC system

Feature		*FSK*	*OOK*
Minimum bit rate above which flicker disappears		60 bps	160 bps
Minimum bit rate at which error appears at the given distance	50 cm	420 bps	160 bps
	100 cm	420 bps	140 bps
	300 cm	380 bps	140 bps
	480 cm	360 bps	120 bps
% improvement of BER for FSK compared to OOK at the given distance and bit rate	50 cm/420 bps	86.8%	--------
	100 cm/420 bps	87.4%	--------
	300 cm/380 bps	93.0%	--------
	480 cm/360 bps	85.3%	--------
Angle at which the BER increases by 10% of that observed at the 0 degree angle for given bit rate	400 bps	3.2°	1°
	460 bps	3.5°	1°

6 Conclusions

This paper presents a way to minimise the effect of low frequency flicker in an experimental VLC system using FSK modulation. The use of FSK modulation in place of OOK improves the BER up to 93% at a distance of 300 cm for 380 bps. Again in terms of angular coverage of VLC, FSK-based modulation provides at least three times improved BER. The FSK VLC setup can reduce the visible flicker up to 60 bps and this can be further improved by increasing the space and mark frequencies. This FSK modulation-based VLC system can be used in the future to achieve efficient monitoring of the slowly varying bio-signals at a much lesser bit rate than the available VLC devices. This will enable a large number of low bit rate devices to be multiplexed and efficiently use the available bandwidth. The VLC setup will also be optimised to enable dimming at the same time. The VLC can also be used exclusively or as components of hybrid communication systems with other wired components (Tiru, 2015) like a power line communication system (PLC). In the future, such an arrangement (PLC-VLC) system is aimed for, to be used in critical environments, especially in hospitals and healthcare centres after solving some of the individual (Tiru and Boruah, 2010; Tiru et al., 2010) and hybrid issues.

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References

Cahyadi, W.A., Jeong, T.I., Kim, Y.H., Chung, Y.H. and Adiono, T. (2015) 'Patient monitoring using visible light uplink data transmission', in *International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS)*, Nusa Dua, pp.431–434, DOI: 10.1109/ISPACS.2015.7432810.

Cailean, A., Cagneau, B., Chassagne, L., Dimian, M. and Popa, V. (2014) 'Miller code usage in visible light communications under the PHY I layer of the IEEE 802.15.7 standard', in *10th International Conference on Communications (COMM)*, Bucharest, pp.1–4, DOI: 10.1109/ICComm.2014.6866699.

Chatterjee, S. and Tiru, B. (2018) 'Optimization of the components of a visible light communication system for efficient data transfer', paper presented at the *2018 IEEE EDKCON Conference*, Kolkata, India, 24–25 November.

Chatterjee, S., Baishya, R., Khan, K., Sarma, P. and Tiru, B. (2018) 'Characteristics of visible light communication using light-emitting diodes', in *Proceedings of the International Conference on Computing and Communication Systems, Lecture Notes in Networks and Systems*, Vol. 24, pp.505–513, Springer, Singapore.

Dimitriou, T. and Ioannis, K. (2008) 'Security issues in biomedical wireless sensor networks', in *First International Symposium on Applied Sciences on Biomedical and Communication Technologies*, Aalborg, pp.1–5, DOI: 10.1109/ISABEL.2008.4712577.

Ding, W., Yang, F., Yang, H., Wang, J., Wang, X., Zhang, X. and Song, J. (2015) 'A hybrid power line and visible light communication system for indoor hospital applications', *Computers in Industry*, pp.170–178, DOI: 10.1016/j.compind.2015.01.006.

Falcitelli, M. and Pagano, P. (2016) 'Visible light communication for cooperative ITS', *Springer Intelligent Transportation Systems*, Vol. 52, pp.19–47, https://doi.org/10.1007/978-3-319-28183-4_2.

Fang, J., Che, Z., Jiang, Z.L., Yu, X., Yiu, S.M., Ren, K., Tan, X. and Chen, Z. (2017) 'An efficient flicker-free FEC coding scheme for dimmable visible light communication based on polar codes', *IEEE Photonics Journal*, Vol. 9, No. 3, pp.1–10, Art No. 7903310, DOI: 10.1109/JPHOT.2017.2689744.

Gayakwad, R.A. (2012) *Op-Amps and Linear Integrated Circuits*, 4th ed., New Delhi, India.

Hosseinianfar, H., Noshad, M. and Pearce, M.B. (2017) 'Positioning for visible light communication system exploiting multipath reflections', in *IEEE International Conference on Communications (ICC)*, Paris, pp.1–6, DOI: 10.1109/ICC.2017.7996815.

Khan, L.U. (2017) 'Visible light communication: applications, architecture, standardization and research challenges', *Digital Communication and Networks*, Vol. 3, No. 2, pp.78–88.

Lee, S.J., Kwon, J.K., Jung, S.Y. and Kwon, Y.H. (2012) 'Simulation modeling of visible light communication channel for automotive applications', in *15th International IEEE Conference on Intelligent Transportation Systems Anchorage*, pp.463–468, DOI: 10.1109/ITSC.2012.6338610.

Li, H., Chen, X., Guo, J. and Chen, H. (2014) 'A 550 Mbit/s real-time visible light communication system based on phosphorescent white light LED for practical high-speed low-complexity application', *Optics Express*, Vol. 22, pp.27203–27213 [online] https://doi.org/10.1364/OE.22.027203.

Li, S., Pandharipande, A. and Willems, M.J.F. (2016) 'Unidirectional visible light communication and illumination with LEDs', *IEEE Sensors Journal*, Vol. 16, No. 23, pp.8617–8626, DOI: 10.1109/JSEN.2016.2614968.

Mejia, C.E., Georghiades, C.N., Abdallah, M.M. and Al-Badarneh, Y.H. (2017) 'Code design for flicker mitigation in visible light communications using finite state machines', *IEEE Transactions on Communications*, Vol. 65, No. 5, pp.2091–2100, DOI: 10.1109/TCOMM.2017.2657518.

Niaz, M.T. and Kim, H.S. (2017) 'Alternative line coding scheme with fixed dimming for visible light communication', *Journal of Physics: Conference Series*, pp.1–6, DOI: 10.1088/1742-6596/787/1/012030.

Oh, M. (2013) 'A flicker mitigation modulation scheme for visible light communications', in *15th International Conference on Advanced Communications Technology (ICACT)*, PyeongChang, pp.933–936.

Okuda, K., Oda, S., Nakamura, T. and Uemura, W. (2014) 'Information delivery tactile pavings using visible light communication', in *IEEE International Conference on Consumer Electronics (ICCE)*, Las Vegas, NV, pp.327–328, DOI: 10.1109/ICCE.2014.6776026.

Paksuniemi, M., Sorvoja, H., Alasaarela, E. and Myllyla, R. (2005) 'Wireless sensor and data transmission needs and technologies for patient monitoring in the operating room and intensive care unit', in *IEEE Engineering in Medicine and Biology 27th Annual Conference*, Shanghai, pp.5182–5185, DOI: 10.1109/IEMBS.2005.1615645.

Periyasam, M. and Dhanasekaran, R. (2013) 'Electromagnetic interference on critical medical equipments by RF devices', in *International Conference on Communication and Signal Processing*, Melmaruvathur, pp.78–82, DOI: 10.1109/iccsp.2013.6577019.

Rajagopal, S., Roberts, R.D. and Lim, S.K. (2012) 'IEEE 802.15.7 visible light communication: modulation schemes and dimming support', *IEEE Communications Magazine*, Vol. 50, No. 3, pp.72–82, DOI: 10.1109/MCOM.2012.6163585.

Siddiqui, B., Pasha, M.A., Naeem, A., Hassan, U. and Jadoon, T. (2015) 'LED-based visible light communication system, for low data rate point-and-grab applications', in *13th International Conference on Frontiers of Information Technology*, pp.258–263.

Suriza, A.Z., Akter, S. and Shahnan, M. (2017) 'Preliminary analysis of dimming property for visible light communication', in *IEEE 4th International Conference on Smart Instrumentation, Measurement and Application (ICSIMA)*, Putrajaya, pp.1–5, DOI: 10.1109/ICSIMA.2017.8312014.

Tan, Y.Y., Jung, S.J. and Chung, W.Y. (2013) 'Real time biomedical signal transmission of mixed ECG signal and patient information using visible light communication', in *35th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, Osaka, pp.4791–4794, DOI: 10.1109/EMBC.2013.6610619.

Tanaka, Y., Komine, T., Haruyama, S. and Nakagawa, M. (2001) 'Indoor visible communication utilizing plural white LEDs as lighting', in *12th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, Vol. 2, pp.81–85.

Tiru, B. (2015) *Intelligent Applications for Heterogeneous System Modelling and Design*, pp.327–340, IGI Global, Hershey, PA, doi:10.4018/978-1-4666-8493-5.ch014.

Tiru, B. and Boruah, P.K. (2010) 'Design and testing of a suitable transceiver for full duplex communication in indoor power line', *IETE Journal of Research*, Vol. 56, No. 5, pp.286–292.

Tiru, B., Boruah, P.K. and Medhi, H. (2010) 'A DSP based channel selecting algorithm for adaptive transmission in indoor power line', *Indian Journal of Physics*, Vol. 84, No. 6, pp.745–749.

Vanderka, A., Hajek, L.M., Latal, J., Vitasek, J. and Koudelka, P. (2015) 'Design, simulation and testing of the OOK NRZ modulation format for free space optic communication in a simulation box', *Advances in Electrical and Electronic Engineering*, Vol. 12, No. 6. pp.604–616.