Visible Light Communications using Organic Light Emitting Diodes

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Abstract—**Organic visible light communications (OVLC) is an emerging subset of visible light communications (VLC) that uses organic photonic components as the link transmitter, receiver or both. Recent developments in organic light emitting diodes (OLEDs) have enabled high efficiency and brightness devices that can be used for data transmission as in conventional VLC systems. VLC utilises the visible wavelength range of the electromagnetic spectrum (370 – 780 nm). Here we demonstrate an OVLC link using an OLED with 93 kHz bandwidth as the source and a silicon photodetector with 5 MHz BW and a 10 dB gain as the receiver. A wide range of modulation schemes are examined and as is commonplace in communications systems; equalization techniques are implemented to maximize data rates into the Mb/s region and 2.7 Mb/s was achieved.**

I. Introduction

Developments in OLEDs have resulted in a great deal of public attention towards the implementation in high end televisions and other display technologies. While OLEDs are ideally suited for use in high resolution displays (low pixel size, high contrast ratio), there is also an exciting application as transmitter in VLC links. VLC, which features ~ 400 THz of license free bandwidth (BW), is becoming popular due to overcrowding of the radio-frequency (RF) spectrum [1]. In VLCs information data is transmitted by modulating the intensity of an optical source operating in the visible range of the electromagnetic spectrum at a rate much faster than the response time of the human eye. The most popular optical source is the conventional LED, because of high optical power and wide BWs. In addition LEDs must also provide illumination over the entire room or office space – therefore arrays of LEDs or large area panels are desirable and have applications in many places such as hospitals. In terms of illumination LEDs are much more power efficient than existing lighting lamps.

There is a wide ranging debate between experts on whether OLEDs will penetrate the solid state lighting (SSL) market for a number of reasons including device lifetime, brightness and organic layer degradation time [2-4] but they all agree that it will be dependent on the cost. OLEDs have the potential to offer extremely low cost manufacturing due to the solubility of the materials, which leads to the ability to print devices using an inkjet printer, roll-on or spray method. However presently, the most popular methods are vacuum deposition or evaporation, requiring very expensive and specialized facilities. Nevertheless, the US Department of Energy has recently tendered a $40 million grant for device development [2] and there is a common belief that OLED based SSL is very much dependent on the display industry and the adoption of OLED displays in order to drive down development costs [2].

Provided this condition is met, OLEDs could very easily be adapted for VLCs, as illustrated in Fig. 1, where OLEDs can be used for lighting and data communications in a number of applications.

Most VLC research is concerned with increasing the data rate and is commonly performed on single LEDs with the premise of 'simply' scaling up the number of LEDs to increase the brightness to ISO standards. However this approach can quickly become overly complex and expensive. A far more suitable method would be to drive a single large area unit, which is not possible with conventional LEDs due to the brittle crystals that are formed using common epitaxial growth methods, which are also expensive. Alternatively, the only restriction in OLED size is due to the dimensions of the fabrication apparatus. There are no limitations on the size of the device itself, which is very promising, thus allowing users to drive the entire large area source from a single input with simple electronics.

OLEDs have a capacitor-like behaviour and exhibit a low-pass transfer function with a cut-off frequency f_c given by:

$$f_c = \frac{1}{2\pi RC} \qquad (1)$$

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where R (Ω) is the effective resistance of the OLED and C (F) is the plate capacitance, given by [5]:

$$C = \frac{A\epsilon_0\epsilon_r}{d} \quad (2)$$

where A (m^2) and d (m) are OLED photoactive area and thickness, respectively, ϵ_0 (F/m) and ϵ_r (unit-less ratio) are the permittivity of free space and relative dielectric constant of the organic layer, respectively. It is clear from (1) and (2) that the device area is inversely proportional to f_c. It is desirable to have a large photoactive area and BW simultaneously, but this represents a significant problem for OLED-VLC. OLEDs with BW > 60 MHz have been produced [6] with $A = 0.018$ mm^2 – clearly too small for illumination of a typical room. Thus there is a need for a solution if OLED-VLC is to be adopted as an emerging technology for both illumination and data communications. Perhaps future high brightness/BW OLEDs will move away from thin films towards nanofabrication as in LEDs [7].

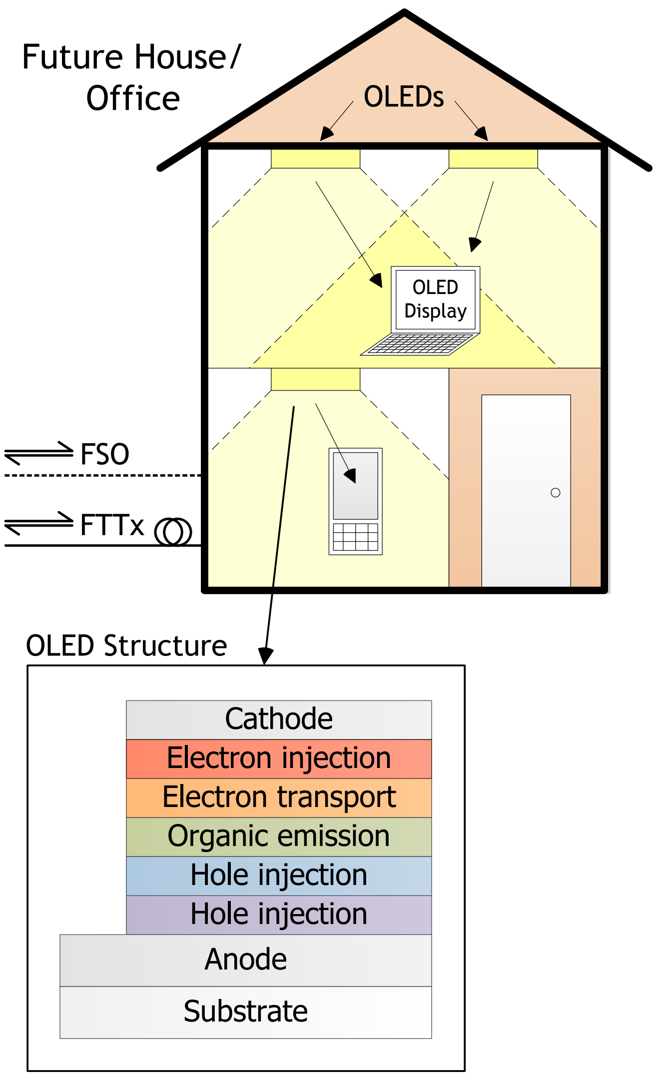


Fig. 1 Future housing, where the link to the local switching centre is provided by free-space optics (FSO) or fibre to the home (FTTx) - large arbitrarily shaped OLED panels (typical structure shown inset) provide data transmission and SSL.

An OLED consists of several layers, see inset in Fig. 1. The substrate, typically glass or plastic, generally followed by a transparent electrode (indium tin oxide), the hole injection and transport layers, an organic emissive layer and electron transport and injection layers. Finally a metallic cathode layer is required to complete the circuit. Typical total OLED thickness is in the order of 1–200 nm, inducing a high capacitance and from (1) a low BW, typically in the order of kHz. This represents a significant problem for communication systems – a restriction in data rate due to the introduction of inter-symbol interference (ISI). When data rate > BW, the system transient response is slower than that of the signal and therefore cannot switch in time causing interference at the sampling instance. Furthermore by the use of coupling capacitors, a baseline wander (BLW) phenomena is introduced that has been experimentally demonstrated to be non-trivial for OLED VLC [8] systems and therefore we introduce a new driving circuit that significantly improves data rate in comparison to previous studies.

A number of methods have been proposed to overcome the small system BW. Firstly, exploiting different modulation schemes offers insight into providing higher data rate without any further signal processing such as equalization or raised cosine filtering, which are the most popular methods of mitigating ISI. Secondly, in common with communications systems, a digital equalizer such as the artificial neural network (ANN) could be used in order to maximize data rate by undoing the detrimental effect of ISI.

Here we demonstrate on-off keying (OOK) and pulse position modulation (PPM) schemes for OLED-VLCs, which are the most popular in VLC, then maximize data rate by employing an ANN based equalizer.

II. OLED Characteristics

OLEDs are Lambertian sources following $I(\theta) = I(0)\cos^m(\theta)$, where I is the luminous intensity (lm/sr), θ is the emissive angle (rads) and m is the Lambertian number. LEDs produce white light with either a package that contains individual red, green and blue (RGB) LEDs or a blue LED that has a yellowish phosphor encompassing the photoactive area, known as white phosphor LEDs (WPLEDs). The most common choice are WPLEDs for two reasons, firstly no colour balancing is required to achieve a constant white hue and therefore the signal processing requirements are less. Secondly, WPLEDs are cheaper than their RGB counterparts. OLEDs only emit white light using the RGB method; however it is possible to stack up the diodes one on top of the other, or place them in succession on the substrate, see Fig. 2(a). No studies have been conducted to find whether either structure has an influence on the device BW to the best of our knowledge. The Osram CMW-031 OLED used here has stacked RGB components. For the optical spectrums of this OLED and a Phillips WPLED see Fig. 2(b).

It is necessary to consider the transfer function of the OLED (known as the L-I curve) to ensure linearity. The L-I curve typically consists of three regions; linear, roll-over and declining as divided by solid vertical lines labelled ‘1’ and ‘2’ in Fig. 2(c). An intensity modulated sine wave is also shown within the linear region of the *L-I* curve.

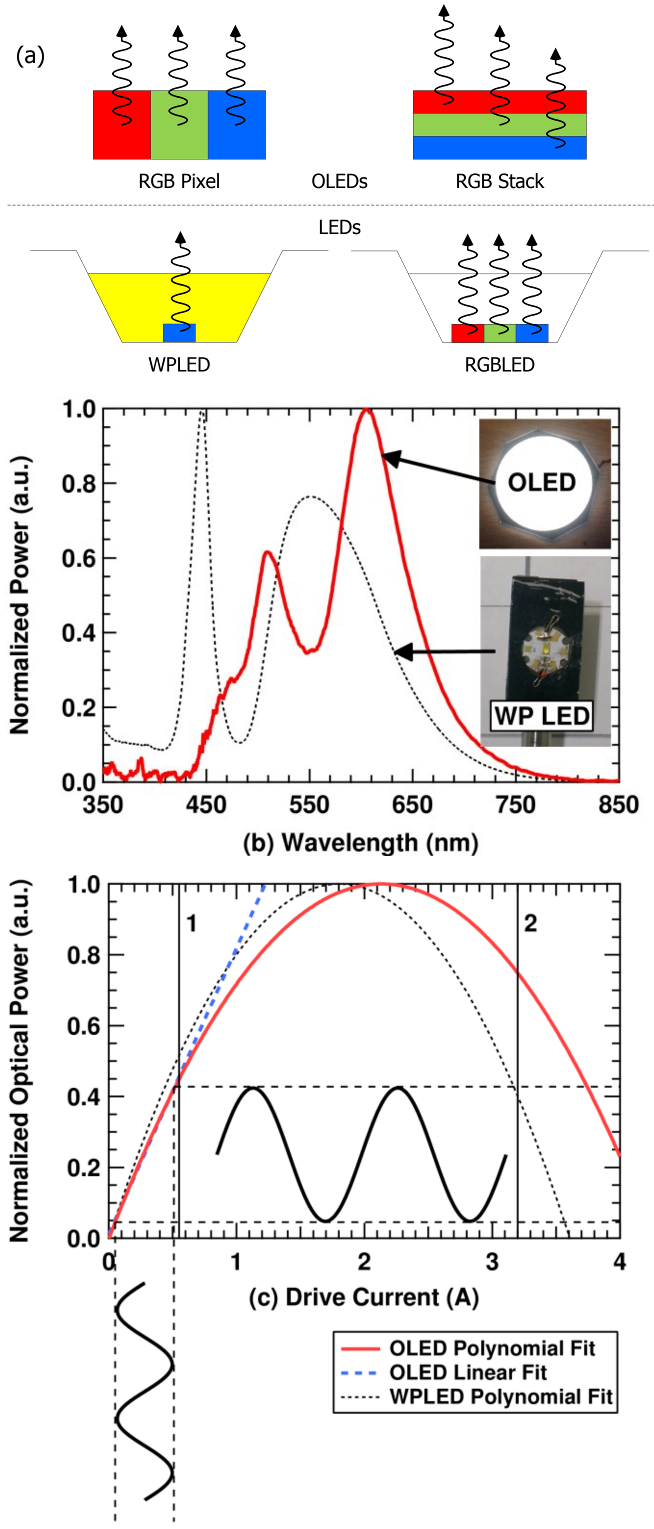


Fig. 2 (a) different methods for producing white light with OLEDs and WPLEDs; (b) OLED (80 mm diameter) and WPLED (2 mm) optical spectrums, the OLED has peaks from RGB superposition at 604 (R), 510 (G) and 470 nm (B). The WPLED has peaks at 445 nm (B) and a wide spectrum with a 550 nm (yellowish) peak. (c) *L-I* transfer functions. The area to the left of the first solid vertical line is the OLED linear region and the data is impressed onto the optical carrier by intensity modulation in the linear region.

To maximize symmetrical swing, the bias current is set to 250 mA from inspection of Fig. 2(c). It should be noted that the *L-I* curve was measured at a wavelengths λ of 510 and 445 nm for OLED and WPLED, respectively. This method of measuring the *L-I* curve is widely adopted. The device efficiency for a given wavelength can also be approximated; a steeper gradient in the linear region indicates better efficiency. In this case WPLED is more efficient than the green component of the OLED. It could be the case, however, that the other components are more or less efficient than both the WPLED and the green OLED component.

A further key characteristic of a communications system is the system BW. A rule of thumb is that the system bottleneck is caused by the device with the slowest transient response. In optical communications there is generally no problem with BW of the drive circuitry, which is a well-developed technology. Due to the thin films and a large photoactive area, the OLED BW is measured to be 93 kHz, however it should be noted that OLEDs with BW > 60 MHz have been produced [6]. The OLED-VLC channel BW can be considered quasi-infinite as the achievable data rate is orders of magnitude lower than the channel bandwidth. Furthermore, considering VLC is most popular in indoor applications, multipath induced ISI is the major problem especially for light sources the wide divergence angle such as OLEDs where light is emitted in all directions. P-I-N silicon photodetectors generally have BWs that are somewhere in the MHz region, depending on the photoactive area just as with OLEDs they also exhibit a capacitor-like behaviour. Furthermore there is also no restriction in transimpedance amplifier (TIA) BWs. The photodetector used here is a ThorLabs PDA36A with transimpedance gain set to 10 dB, which restricts the overall receiver BW to 5 MHz, which is still relatively large in comparison to OLED under test.

III. Modulation Schemes and Driving Circuits

Here we have adopted OOK and PPM (see Fig. 3) for two reasons; ease of implementation and their spectral characteristics. OOK is the most BW efficient modulation scheme while PPM is the most power efficient and also possesses little spectral components around the DC region. The order of PPM can be increased to *M*-PPM at the cost of additional BW by introducing more slots (slot number must be a power of 2, otherwise capacity is wasted) into the symbol period. The mathematics for these modulation schemes and their BW requirements can be found in [9].

The BW requirement for OOK is equal to the data rate where the first spectral null lies, while 2-PPM (the most simple order of PPM recalling the requirement that the symbol period has to be split into *L*-slot) requires at least twice the BW of OOK for the same data rate due to the increased switching time caused by splitting the symbol period. For 2- and 4-PPM the BW requirement is the same, however as *M* increases (8, 16, 32, …), the BW requirement also increases linearly as can be seen mathematically in [9]. For this reason high orders of PPM are rarely considered in band limited systems and here we only demonstrate 2- and 4-PPM as well as OOK. It should be noted that while OOK and M-PPM can both be demodulated using the simple threshold-detection scheme, the so-called 'soft demodulation' where the incoming data stream is reshaped into an M-column matrix can be used for M-PPM. Since each slot only contains a single 1-level pulse then the highest valued matrix element is assigned a 1-level and the remaining elements are assigned the 0-level. Using this method over threshold-detection offers an electrical signal-to-noise ratio (SNR) gain of 1.5 dB [10].

The driving circuit for the optical source has a large impact on the performance of any modulation scheme adopted. For instance, using the circuit in Fig. 4(a) in conjunction with OOK a significantly lower data rate can be achieved compared to the circuit in Fig. 4(b). The link performance is measured in terms of the bit error rate (BER). This can be calculated or estimated in a number of ways, including measuring the Q-factor using the eye-diagram or comparing transmitted and received bits. Q-factor analysis is only valid for systems that are perturbed exclusively by additive white Gaussian noise (AWGN). VLC systems experience AWGN; however this system is also influenced by BW limitation, which is not a random effect, so to measure the performance in this way would be unfair and thus transmitted and received bits are compared.

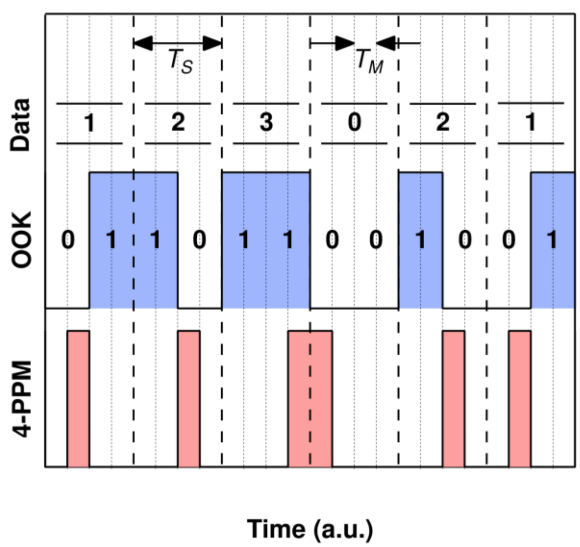


Fig. 3 OOK and 4-PPM modulation schemes, T_s and T_M denote symbol and slot periods, respectively. Here there are two bits/symbol (P = 2) and hence the number of PPM slots $M = 2^P = 2^2 = 4$ slots. The pulse is positioned according to the data.

Fig. 4(c) shows the BER plots for the two driving circuits, illustrating a significant improvement with the NAND driver over the bias-tee driver. Incidentally, the term error free corresponds to a BER of 10^{-6} as is commonly accepted in optical communications [8]. Some insight into the data rate increase can be provided by considering the frequency spectrum of each driver. In bias-tee driver, the selection of capacitor is crucial as it has an associated cut-on frequency f_{co}. If the SYMBOL capacitor value is selected to be high the cut-off frequency is reduced (which is desirable) but more power is dissipated meaning that the modulation depth decreases. Improperly selecting too low means f_{co} increases, inducing the BLW phenomena as the DC and low frequency components below f_{co} are significantly attenuated. BLW is where the signal envelope drifts randomly from the DC power level. There have been studies to try and eliminate BLW such as the quantized feedback baseline restoration, which aims to restore the missing frequency components with a feedback filter, or using a subcarrier frequency in order to avoid the signal attenuation. This method in particular is not ideal as it wastes the available BW, thus reducing system capacity. It is noteworthy that BLW is not a random Gaussian process [11] so it is not trivial to recover the original signal envelope and hence there is no ideal solution to date.

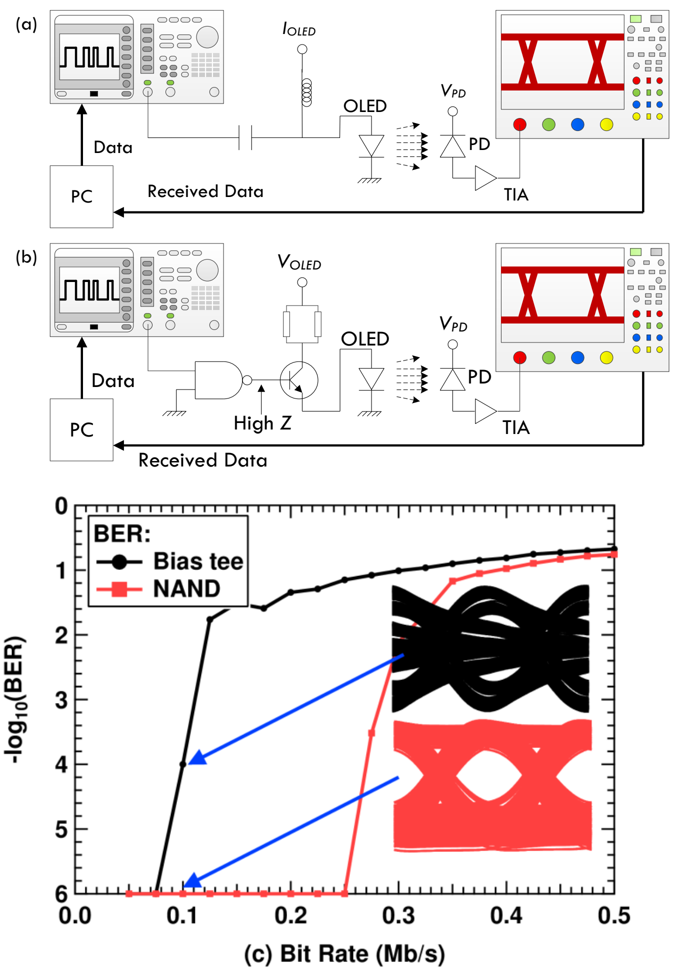


Fig. 4 Two possible driving circuits for an OLED-VLC system: (a) the bias-tee; (b) a NAND driver; and (c) the BER vs the bit rate.

By isolating the AC data source using a high impedance (denoted high Z in Fig. 4 (b)) NAND, there are no low frequency restrictions and therefore no BLW effect. It is for this reason that the data rate can be extended. In addition, the modulation depth increases from < 10 % in bias-tee driver up to ~ 100 % in the NAND driver as no power is dissipated through components, thus significantly improving SNR at the receiver, which is also a major factor in the improvement. The advantage of bias-tee driver is that it is not restricted to digital pulse modulations; analogue formats and multi-level digital formats such as pulse amplitude modulation could be adopted, which is not possible with the NAND driver. Since we are not demonstrating analogue or multi-level modulations we have used the NAND driver.

When using threshold-detection, the performance of OOK far surpasses that of 2- and 4-PPM, Fig. 5. It is clear that the reason OOK outperforms *M*-PPM with the bias-tee driver is due to the lower BW requirement – E.g. at 50 kb/s with 4-PPM, 100 kHz BW is required. For data rate above this, the system cannot provide the required transient response. Interestingly, 2-PPM can successfully transmit 150 kb/s requiring 300 kHz BW, which far exceeds the system BW. The reason for this is due to the capacitor-like behaviour of OLED. Recalling that 2-PPM symbols must contain a single 1-level and 0-level, the maximum number of similar consecutive levels is two. Therefore OLED remains in a steady state of pseudo-oscillation, i.e. it is never fully on/off. For higher data rate the ISI becomes dominant and threshold-detection fails.

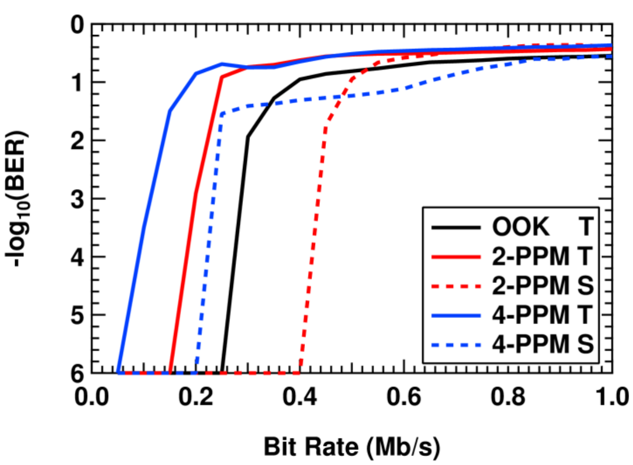


Fig. 5 BER comparison of OOK, 2- and 4-PPM using threshold-detection (denoted T) where the achievable data rate is 250, 150 and 50 kb/s, respectively. When using soft (S) demodulation, data rate can be extended to 400 and 200 kb/s for 2- and 4-PPM, respectively, offering an increase of 150 and 250 kb/s.

Soft demodulation offers a limited solution to this problem, which is reflected in the increased data rate for *M*-PPM. By reshaping and assigning the digital levels, the reliance on the threshold is removed and the system BER performance is dominated by the signal gradient at the sampling instances. Note that at data rate of 400 for 4-PPM offers a significant improvement over OOK.

IV. Neural Networks for Equalization

Equalizers are the most effective way of overcoming ISI in communication systems. There are many different equalizers that offer varying complexity and performance. A brief overview of non-neural equalizers is given before ANNs are introduced. Non-neural equalizers are not the focus of this work and no theory is given although it is well covered in [9].

The simplest equalizer is high pass filter resistor-capacitor (RC) equalization. The mathematics can be seen in [12], while recalling that the attenuation of low frequency components causes BLW and threshold-detection to fail. Nevertheless, using post-equalization in conventional VLC systems has shown a remarkable increase in achievable data rate up to 100 Mb/s [12] while in OLED-VLC it is not possible to sustain any significant error free data rate due to the impact of the BLW phenomena. The reason for this is the difference in capacitance between the two devices leading to BWs that are significantly different (OLED: 93 kHz, WPLED: ~ 4 MHz). For example, by using the same RC filter for both systems, a greater proportion of the system frequency response is removed for the OLED system. Hence BLW is more severe while WPLED is operating at data rate that far exceeds the RC f_{co}, thus BLW has less impact on data recovery.

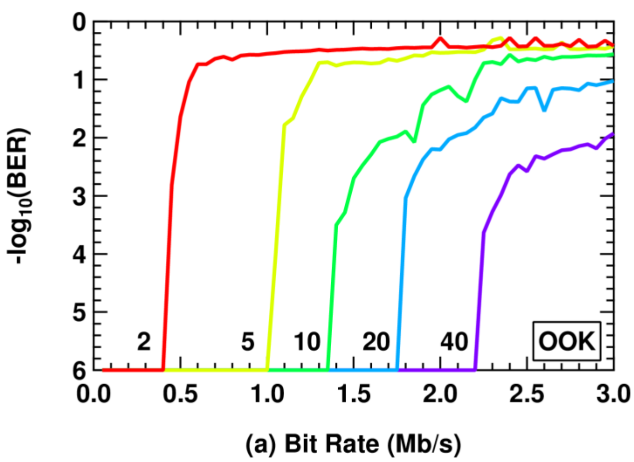
The digital domain offers an increase in performance at the cost of increased complexity. There are many digital equalizers but the decision feedback equalizer (DFE) is the most popular option due to superior performance and ease of hardware implementation [13]. DFE is a non-linear adaptive equalizer that consists of two finite impulse response (FIR) filters that are made up of tap delay lines, one is feedforward, the other is feedback. The filters are used to map the system transfer function and hence a training sequence is required before use. Training is the transmission of a bit sequence known at the receiver in order to estimate the channel response. The estimation quality is dependent on the number of filter taps. Increasing the number of taps increases the performance at the cost of complexity and training convergence time. Once known, the useful information is transmitted.

DFE is similar to an ANN, which is comparable to the human mind. It has neurons, synapses and ability to learn based on reducing errors compared to a frame of reference. Synapses (i.e. FIR filter taps) are the input to the neuron. Increasing the number of synapses improves the system representation. The computation happens in neurons, which are divided into a highly parallel structure allowing non-linear problem solving by adaptively adjusting the impact or contribution (i.e. the weight) of individual neurons. This is a particular advantage because the system response is often non-linear as is the case for bandlimited systems. Increasing the neurons increases the learning capacity of the ANN at the cost of increased complexity. Generally the number of taps can be set equal to the number of neurons.

For channel equalization the multilayer perceptron (MLP) is the most popular choice and hence will be demonstrated here [13]. Other ANNs that offer greater performance are available, such as the functional link ANN (FLANN) or the radial basis function ANN (RBF), however the two latter require a much greater level of complexity so are not commonly used for equalization but can be referred to in [13, 14]. MLPs can be linear or DF; linear MLPs only have a feedforward filter while DF-MLPs also have a feedback filter. The difference between MLPs and DFE is the subtraction between the two filters; instead MLPs have a 'black box' (known as the hidden layer) performs a gradient descent on the error cost function, the mathematics of which can be found in [13, 14].

In order to learn the input-output sequence the ANN requires training just like DFE, where supervised or unsupervised training can be adopted. This can be likened to learning from a book (unsupervised) or being taught by a teacher (supervised). The most popular choice is the Levenberg-Marquardt back-propagation algorithm, which is supervised training because it is simple and easy to implement in hardware [13]. It works by taking the training set and the input vector then updating the neuron weights iteratively until the error between the equalized data and the target data does not exceed an objective error separation. The rate at which the ANN learns is selected adaptively [15]. ANNs have a significant advantage over DFE – the capability to generalize. This is a key advantage because it means that if an error occurs that was not in the training sequence, ANN will not fail when DFE will, thus increasing the BER in comparison [13, 14].

The BER performance of the MLP with the tap (and neuron) number varying in the set {2, 5, 10, 20, 40} is shown in Fig. 6(a), (b) and (c) for OOK, 2-PPM and 4-PPM, respectively. It is clear from all three modulation schemes that the performance increases with the tap/neuron number. The performance will not continue to increase infinitely, however as eventually a saturation data rate will be found. This is not shown explicitly in Fig. 6 because an excessive number of taps would be required. Data rates that can be achieved using the MLP-ANN are 2.7, 2.2 and 1.25 Mb/s for 4-PPM, OOK and 2-PPM, respectively. In comparison to the non-equalized system each of these data rates are significantly higher, illustrating the power of MLP as an equalizer.



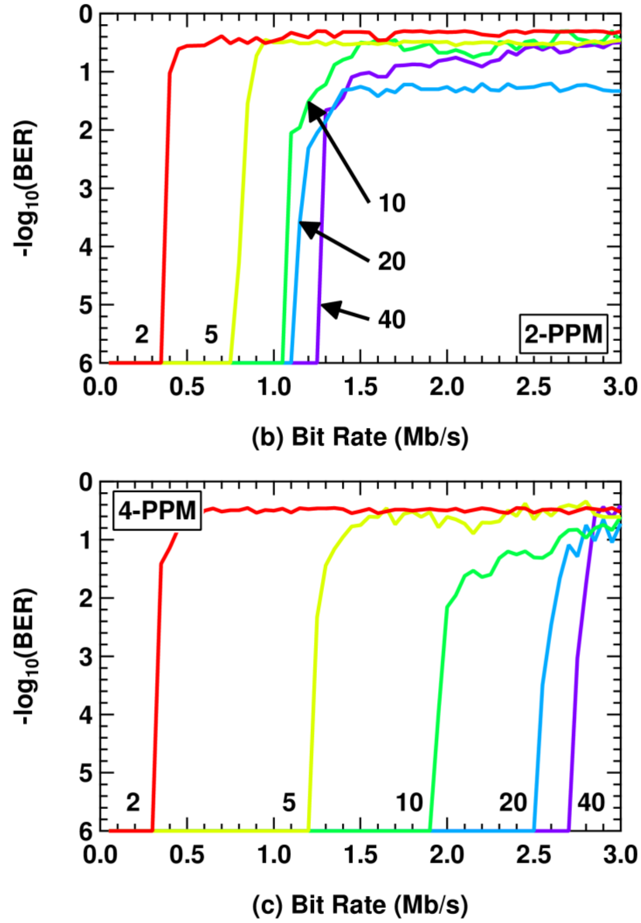


Fig. 6 BER performance: (a) OOK, (b) 2-PPM, and (c) 4-PPM with a number of delay tap lines and neurons.

V. Future Outlook and Conclusion

OLEDs are a very interesting candidate for future VLCs. However, there are a number of significant challenges to overcome first and most of them lie in the physical and chemical domain and concern key characteristics such as the device lifetime, structure, degradation of the organic layers. The most important concern at the time of writing is the cost which is heavily dependent on the progress of OLEDs in displays. Using MLP-ANN we have demonstrated data rate of over 2.5 Mb/s using an OLED with a low BW. The next target should be 10 Mb/s in order to achieve the lowest standard Ethernet (10-baseT). This data rate could easily be achieved using a device of higher BW such as 60 MHz OLED in [6]. A possible way to overcome this would be to place a large number of 60 MHz diodes on the same substrate driven by the same source in order to produce a large photoactive area by aggregation. If these fundamental building blocks are achieved then there is no reason why OLEDs should not take off as a very important technology in VLCs and SSL. Furthermore the electronics requirements are easily met and well developed, however miniaturization is not well developed for VLCs and this would also be required for commercialization of the technology.

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