A 10 Mb/s Visible Light Communication System using a Low Bandwidth Polymer Light-Emitting Diode

Invited Paper

P. A. Haigh[1,2], F. Bausi[3,4], T. Kanesan[5], S. T. Le[6], S. Rajbhandari[7], Z. Ghassemlooy[1], I. Papakonstantinou[2,4], W. O. Popoola[8], A. Burton[1], H. Le Minh[1], A. D. Ellis[6] and F. Cacialli[3,4]

[1]*Optical Communications Research Group, Northumbria University, Newcastle-upon-Tyne, NE1 8ST, UK*
[2]*Department of Electronic and Electrical Engineering, University College London, WC1E 6BT, UK*
[3]*Department of Physics and Astronomy, University College London, WC1E 6BT, UK*
[4]*London Centre for Nanotechnology, University College London, WC1E 6BT, UK*
[5]*Telekom Research and Development Sendirian Berhad (TM R&D), TM Innovation Centre Lingkaran Teknokrat, 63000 Cyberjaya, Selangor, Malaysia*
[6]*Aston Institute of Photonic Technologies, Aston University, Birmingham, B4 7ET, UK*
[7]*Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK*
[8]*School of Engineering and Built Environment, Glasgow Caledonian University, Glasgow, G4 0BA, UK*
**Corresponding author: paul.anthony.haigh@ieee.ac.uk; f.bausi@ucl.ac.uk; let1@aston.ac.uk*

***Abstract*—In this paper we experimentally demonstrate a 10 Mb/s error free visible light communications (VLC) system using polymer light-emitting diodes (PLEDs) for the first time. The PLED under test is a blue emitter with ~600 kHz bandwidth. Having such a low bandwidth means the introduction of an inter-symbol interference (ISI) induced penalty at higher transmission speeds and thus the requirement for an equalizer. In this work we improve on previous literature by implementing a decision feedback equalizer, rather than a linear equalizer. Considering 7% and 20% forward error correction codes, transmission speeds up to ~12 Mb/s can be supported.**

***Keywords*— Equalizers, organic light emitting diodes, visible light communications, intersymbol interference, bit error rate**

I. INTRODUCTION

VISIBLE light communications (VLC) using organic polymer light-emitting diodes (PLEDs), with soft lighting, is emerging as a serious candidate for future smart monitors, display, and screens. Current display technologies often utilize liquid crystal displays (LCDs) which have a number of considerable disadvantages including a poor contrast ratio, slow switching times and the requirement for additional components such as colour filters and LED backlighting. PLEDs offer solutions to all of these problems and also have several key advantages such solution-based processing methods at room temperatures, mechanical flexibility, crisper displays as well as producing light at a very wide range of wavelength. Additionally PLEDs use less power than conventional LEDs or LCDs used today. Since PLEDs are a light source they do not require an additional backlight like LCDs which results in higher power efficiency. This is especially important for battery-operated devices such as cell phones. Patterning such devices into an individually addressable active matrix would enable a massively multiple-input, multiple-output (MIMO) high-speed access point, providing connectivity to ubiquitous VLC home/office networks whilst simultaneously offering monitoring functionality.

Fig. 1 shows the structure of the PLEDs used in this work, composed of a number layers including transparent conducting anode, hole injection layer, emissive layer and the top electrode.

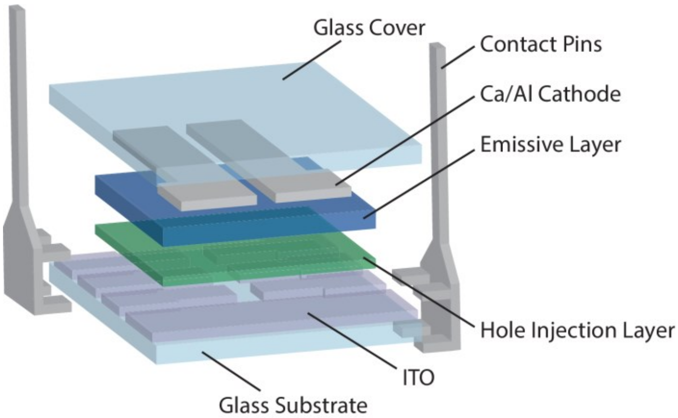

Fig. 1 Structure of the PLEDs used in this work

In order to fully render the required gamut of colours, red, green and blue (RGB) pixels are required; with each colour requiring a high transmission speed to achieve the best possible capacity. In the literature, a 10 Mb/s PLED-VLC system using a single low bandwidth (270 kHz) PLED was demonstrated experimentally in [1, 2]. The emissive polymer used was poly[2-methoxy-5-(3′,7′-dimethyloctyloxy)-1,4-phenylenevinylene] (MDMO-PPV), which is an orange/red emitter. Due to the lower bandwidth (i.e. 270 kHz) capability, a linear least mean squares (LMS) adaptive equalizer was required to increase its bandwidth range suitable to communication applications. Having a low bandwidth is an inherent problem in polymer-based VLC (PVLC) owing to typical low charge transport mobility (10^{-7}-10^{-3} cm^2/V s) of polymer semiconductors [3]. The bandwidth is also limited by the parallel capacitance associated with the devices due to their large area (~3 mm^2) and small thickness (~200 nm). Thus, the VLC systems using PLEDS depend strongly and primarily on ISI mitigation techniques such as equalizers or alternatively spectrally efficient modulation formats such as orthogonal frequency division multiplexing (OFDM). To date there are no works that have been reported on OFDM based PVLC in the literature, however in an inorganic VLC OFDM has been used to achieve extremely high transmission speeds in the Gb/s region from limited modulation bandwidths [4, 5].

In this work, we propose to extend the transmission data rate previously reported using a decision feedback equalizer (DFE). Unlike linear adaptive equalizers, DFEs are capable of calculating non-linear system response characteristics using a feedback channel, thus resulting in a ~ 3 dB signal-to-noise ratio (SNR) gain, considering an equal number of taps and minimum mean square linear equalizer structure [6]. Furthermore, the PLED bandwidth in this work is extended to 600 kHz by using a blue-emitting polymer, details to follow in Section II. An extended bandwidth enables an increase in error free (10^{-6}) transmission speed up to 10 Mb/s, which is more than sufficient for supporting a live Ethernet connection in a point-to-point link.

II. Polymer Light Emitting Diode Processing

The light-emitting devices used in this work are encapsulated between two glass slides and sealed with an epoxy-resin to preserve them against degradation during test procedures. Semiconducting polymers can undergo oxidation when in contact with oxygen and water from air [7]. Moreover, the metallic calcium cathode can easily react with water. Both these processes decrease the efficiency of the devices. Encapsulation increased the LEDs lifetimes and allowed us to use them in air. For the preparation of the devices, we started from a glass substrate with a thin layer (~110 nm) of a conductive transparent indium tin oxide (ITO) as the anode (Ossila Ltd). The transparent electrode is pre-patterned to give 6 independent LEDs. We cleaned the ITO by 2 cycles of sonication in acetone and IPA. An oxygen plasma treatment (10 minutes) was carried out to reduce the roughness (RMS ~ 2 nm) and increase the work function [8, 9].

Afterwards, we deposited a hole-injection layer (40 nm) of PEDOT:PSS (Heraeus CleviosTM P VP AI 4083) via spin-coating (5000 rpm for 30 s in air). It consists of a water dispersion of poly(3,4-ethylenedioxythiophene) (PEDOT) doped with poly(styrenesulfonic acid) (PSS) that features conductivities in the range of 0.2-2 10^{-2} S/cm and a high work function (~ 5.2 eV [9]) to improve the hole-injection at the interface with the active layer. The samples are then annealed at 150 °C for 10’ in nitrogen atmosphere to remove water residues and improve the hole-injection performances.

The light-emitting layer is a blend of three blue-emitting polyfluorenes: poly(9,9-dioctylfluorene) (F8), (poly(9,9-dioctylfluorene-alt-N-(4-butylphenyl) diphenylamine) (TFB), poly(9,90-dioctylfluorene-alt-bis-N,N0-(4-butylphenyl)-bis-N,N0-phenyl-1,4-phenylenediamine) (PFB) in ratio 1:2:2 in a 2% w/w solution in mixed xylenes (Sigma-Aldrich).

The polymer blend was deposited via spin-coating (2000 rpm for 60 s) and the samples were annealed at 150 °C for 10’ in nitrogen to increase the molecular packing and hence the charge carrier mobility inside the polymer active layer. As a final step we deposited the metallic cathode by evaporating a thin (30 nm) layer of calcium covered by a protective layer (150 nm) of aluminium. Then we encapsulated the devices by applying a protective glass slide using a UV-hardened epoxy-glue (Ossila Ltd) (curing is done with a low power UV lamp 4 mW/cm^2 for 15 minutes in nitrogen).

III. Optoelectronic Characterisation

The PLED normalized electroluminescence (EL) emission is shown in Fig. 2. This features two peaks at ~ 480 nm and 624 nm, significantly red-shifted with respect to the emission of all three components. While the emergence of “green emission bands” is well documented in the literature and attributed to a combination of ketone-defects and inter-chain effects [10], we consider that the relatively large red-shift of the second peak, that is observed in these spectra is likely to be related to formation of exciplex species between some of the polyfuorenes. The frontier energy levels of these materials are so close that it is hard to identify which specific polyfluorene is involved in the formation of this excited state and as such, further investigations are in progress.

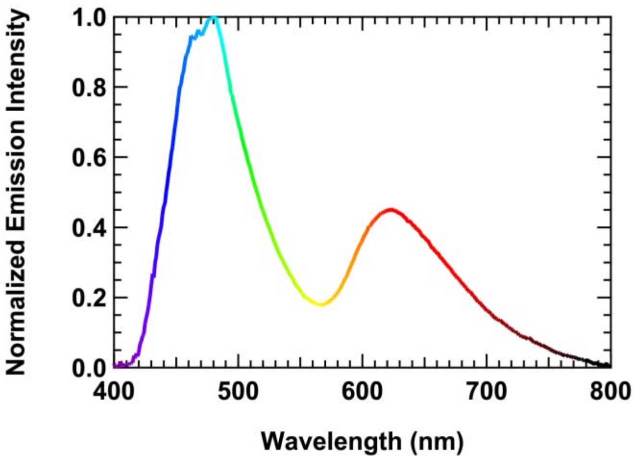

Fig. 2 PLED normalised emission intensity showing two peaks at 480 nm and 624 nm

The PLED light-current-voltage characteristics are shown in Fig. 3 and were measured using a Keithley 2400 current/voltage source and Keithley 2000 digital multi-meter. The characteristics shown are very similar to the results outlined in [11]. The PLED initially exhibits a linear light-current relationship up to ~8.5 mA. The current-voltage relationship can also be approximated by a linear relationship for currents above ~2.5 mA, as shown on the plot, and hence the bounds for information transmission are established. The bias current I_B is set equidistant between the two limits at 5.5 mA, thus setting the modulation current I_M = 6 mA peak-to-peak in order to avoid electrical clipping at the 0-level and optical clipping at the 1-level.

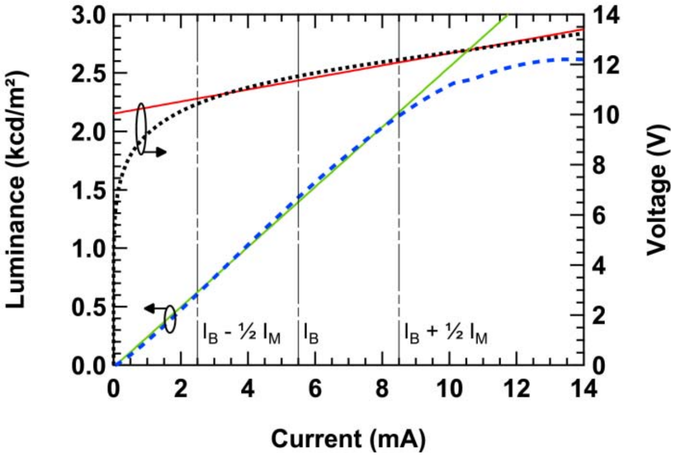

Fig. 3 The PLED L-I-V curve showing a clear linear region (fits shown as solid lines, measured data as dashed lines) with annotations showing the current bias and modulation points; the PLEDs have area ~3 mm^2

The measured bandwidth and system noise floor are both illustrated in Fig. 4, which shows a 3-dB bandwidth of ~600 kHz; roughly 330 kHz larger than was reported in [1, 2]. There is probably a combination of reasons for this, but we consider that differences in the hole and electron populations (and balance) as a result of differences in the injection barriers and mobilities (expected to be higher in polyfluorenes than in PPVs)[3] are likely to be the most important factor here, although we cannot rule out "apparently minor" changes of the contact resistance that will greatly affect the overall RC time constant of the circuit.

IV. TEST SETUP

The schematic block diagram of the experimental set-up for the proposed system is illustrated in Fig. 5. Also shown is a photograph of a single illuminated pixel inset. A 2^{10}-1 pseudorandom binary sequence (PRBS-10) is generated in MATLAB and formatted into the OOK modulation scheme with a unity height rectangular pulse shaping filter before being passed through an integrated current mirror and amplifier drive circuit that sets I_B and I_M appropriately (refer to Fig. 3), thus intensity modulating the PLED.

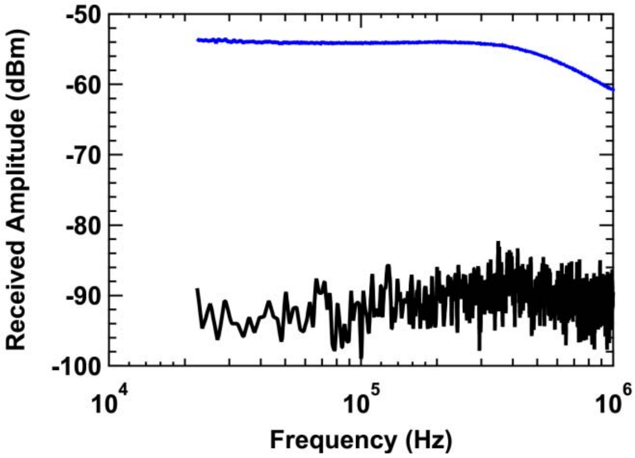

Fig. 4 The measured PLED frequency response (blue) and system noise floor (black), measured with an Agilent N9010A electrical spectrum analyzer

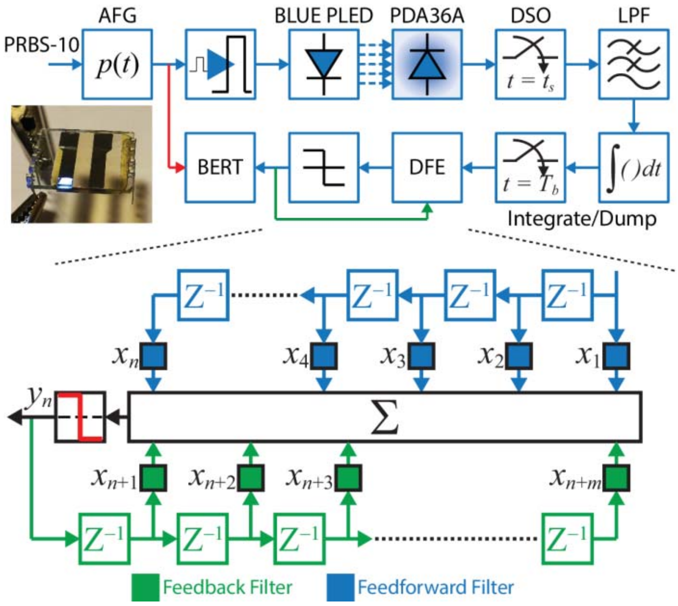

Fig. 5 Schematic block diagram of the proposed system under test, including expanded DFE structure

The PVLC channel can be mathematically described as a less-than-unity DC gain that is not frequency selective for the transmission speeds concerned [12]. In fact, the bandwidth of the channel is orders of magnitude larger than that of the PLED. The transmitter/receiver distance in this work is set to 0.05 m due to use of a single pixel. This is also in line with [1, 2]; if a larger distance is required more pixels can be illuminated to increase the optical intensity.

The receiver consists of a ThorLabs PDA36A silicon photodetector and a packaged transimpedance amplifier of 10 dB with an overall bandwidth of 5.5 MHz. The received continuous time signal is sampled by an Agilent DSO9254A real time oscilloscope, which acquires at least 10^7 data samples at a sampling rate of at most 10 Sa/sym, depending on the data rate.

The signal is then processed in MATLAB starting with a 4th order low pass filter to remove the out-of-band noise. Next the symbols are down-sampled using an integrator and dump (i.e. the matched filter) receiver prior to the symbol spaced DFE equalization module. The mathematics of the DFE are well known and can be referred to in [13]. The DFE implementation considers two finite impulse response (FIR) filter banks (feedforward and feedback) consisting of inputs and tapped-weight coefficients and a threshold comparator as illustrated in Fig. 5.The DFE requires training and the recursive least squares (RLS) algorithm is selected in this work (refer to [14]) with a forgetting factor $\xi = 1$, meaning that every previous symbol is considered during the training process. The number of taps must be selected according to the ISI span, which is unknown at the symbol arrival time. To the best of the author's collective knowledge, there is no algorithm that is capable of predetermining the optimal number of taps. Therefore it is either necessary to start with a large number of taps and gradually reduce them, or vice-versa. Furthermore, in general the maximum number of feedback taps T_{fb} is set to $T_{fb} = \lfloor T_{ff}/2 \rfloor$, where T_{ff} is the number of feed-forward taps and $\lfloor . \rfloor$ is the floor function in order to avoid long error propagation. The equalized symbols are passed through the threshold based comparator and compared with the transmitted symbols for error rate calculation. The number of taps under examination in this work are [T_{ff}, T_{fb}] = {[5, 2]; [10, 5]; [15, 7]; [20, 10]; [30, 15]}, which will provide insight into the improvement that can be obtained using an increasingly complex system. Although the DFE is implemented in MATLAB, it is still necessary to consider future hardware implementation of both the equalizer [15] and the RLS training method [16] and the relevant requirements are shown in Table I.

Table I
Theoretical DFE hardware requirements from [15]; $N = T_{ff}$ or T_{fb}

DFE requirement	T_{ff}, T_{fb}	5, 2	10, 5	15, 7	20, 10	30, 15
Additions	$2M^{N/2}$	12, 4	64, 12	363, 23	2048, 64	65536, 363
2-to-1 Multiplexers	$2M^{N/2}$-2	10, 2	62, 10	361, 21	2046, 62	65534, 361
Multipliers	0	0	0	0	0	0

As mentioned, the RLS algorithm is selected for training. The RLS algorithm offers a faster convergence to a lower mean square error than the LMS algorithm. The relative hardware requirements are illustrated in Table II. The complexity is a relative term because the absolute hardware requirement (i.e. number of flip-flops, look-up tables, etc.) depends on the fixed point resolution which is not considered here.

V. Results

The unequalized BER results are shown in Fig. 6 with eye diagrams inset for transmission speeds of 1 Mb/s and 3 Mb/s, respectively. An error free (10^{-6}) link can be achieved at transmission speeds up to 3 Mb/s. The power penalty due to the limited modulation bandwidth is evident in the Q-factor analysis, which shows a substantial reduction with increasing transmission speeds; at 1 Mb/s the Q-factor is ~30 dB while at 3 Mb/s the Q-factor is reduced to ~7.2 dB. For transmission speeds >3 Mb/s, the ISI penalty is too great and no useful transmission can be supported.

Table II
Theoretical RLS hardware requirements from [16]; $N = T_{ff}$ or T_{fb}

RLS requirement	T_{ff}, T_{fb}	5, 2	10, 5	15, 7	20, 10	30, 15
Multipliers	$5N^2$+$5N$	150, 30	550, 150	1200, 280	2100, 550	4650, 1200
Additions	$4N^2$	100, 16	400, 100	900, 196	1600, 400	3600, 900
Divisions	N	5, 2	10, 5	15, 7	20, 10	30, 15

In order to improve the transmission speed the DFE is required to remove the ISI from the signal and restore error free performance. The DFE BER performance is therefore illustrated in Fig. 7. Using [30, 15] tapped weights a transmission speed of 10 Mb/s can be supported at a BER of 10^{-6}. The same transmission speed can be achieved at the same BER using [20, 10] taps with a substantial reduction in hardware complexity of more than two times (refer to Table I and Table II), which is advantageous. This report of 10 Mb/s is the highest reported error free transmission speed in PVLC to the best of the authors' knowledge. The previous record was established at 7 Mb/s in [1, 2]. By reducing the number of taps to [15, 7; 10, 5; 5, 2], transmission speeds of 9, 8 and 7 Mb/s are supported, respectively. Transmission speeds can be improved by considering conventional forward error correction (FEC) codes such as turbo codes or low density parity check codes (LDPC) [17]. In this work we consider two FEC codes that are common in high speed VLC systems [4] with 7% (BER limit = 0.0038) and 20% (0.02) overheads, respectively.

Using the 7% FEC with [30, 15] taps, an overall line rate of 12.09 Mb/s can be supported, offering a 2.09 Mb/s improvement over the error free (10^{-6}) case. Considering the 20% limit, a gross transmission speed of 15 Mb/s can be supported that is reduced to 12 Mb/s after overhead removal.

Similar results can be achieved using [20, 10] taps. Considering the 7% FEC limit, a gross data rate of 12 Mb/s can be supported (at 12 Mb/s equalized BER of 0.00495, slightly exceeding the limit, but substantially closer than 11 Mb/s) leading to a line rate of 11.16 Mb/s. When considering a 20% FEC, 12 Mb/s can be achieved, which is equal to [30, 15] taps with substantially reduced hardware requirements.

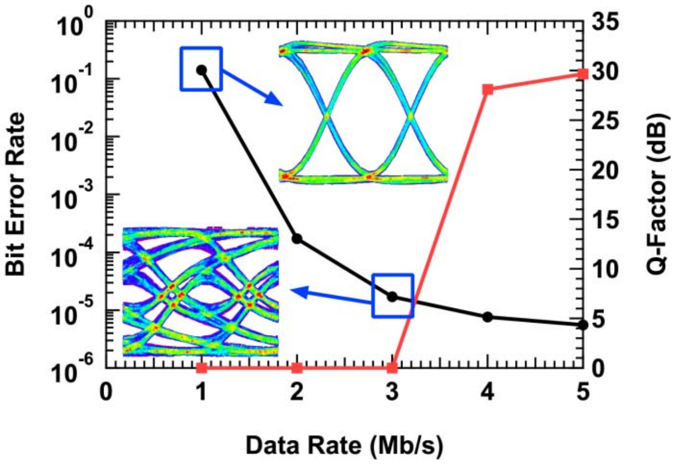

Fig. 6 Unequalized BER performance (left, red) and Q-factor (right, black) of the link with eye diagrams at 1 Mb/s and 3 Mb/s, respectively. Transmission speeds up to 3 Mb/s can be supported

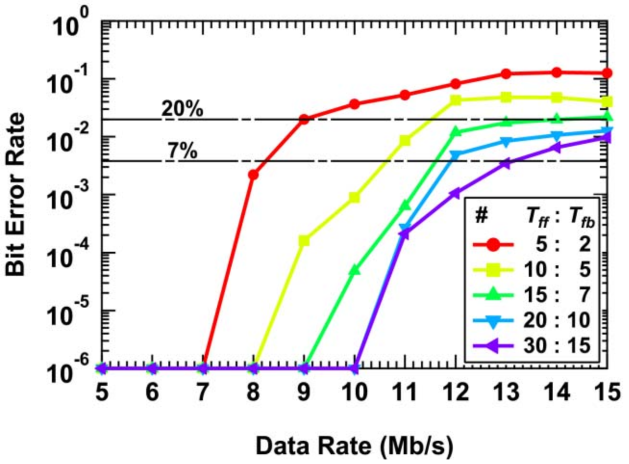

Fig. 7 Equalized BER performance using the DFE with a varying number of taps; error free transmission speeds up to 10 Mb/s are available

For [15, 7] taps, an equalized error free transmission speed of 9 Mb/s can be supported as mentioned. When considering the 7% FEC this is improved to at least 10.23 Mb/s after overhead removal while using the 20% FEC allows a transmission speed of 11.2 Mb/s. For the [10, 5] tap case, the transmission speed drops beneath 10 Mb/s for the first time to 9.3 Mb/s and 8.8 Mb/s using the 7% and 20% FECs, respectively. Finally when using [5, 2] taps, the maximum available transmission speeds are 7.44 Mb/s (7%) and 7.2 Mb/s (20%).

Considering the maximum speed available for any number of taps tested here is 12.09 Mb/s, it would not be recommended to use [30, 15] taps in a future hardware implementation. Using [20, 10] taps with a 20% FEC can provide a transmission speed of 12 Mb/s, offering 99.2% of the available speed of the [30, 15] tap system but with less than half of the hardware requirements.

VI. CONCLUSION

In this paper we have demonstrated a PVLC system that is capable of error free transmission at 10 Mb/s for the first time. Due to the limited modulation bandwidth (~600 kHz) of the polymer which restricts transmission speeds, a DFE was required to remove the ISI present in the system. The transmission speed can be improved further when considering FEC codes, allowing a 12.09 Mb/s system to be achieved.

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