Organic Photovoltaics for Simultaneous Energy Harvesting and High-Speed MIMO Optical Wireless Communications

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Supplementary Information

Supplementary Figures and Tables

Figure S1: Comparison of indoor lighting spectra (from white LED and fluorescent lamp) with the AM 1.5 G solar spectrum.

Figure S2: Absorption spectra of the three OPV active layer blends used in this study (a) PTB7:PC_{71}BM, (b) PTB7-Th:PC_{71}BM, (c) PTB7-Th:EH-IDTBR.

Table S1: Solar cell performance parameters of the three OPV active layer blends used in the present study under solar spectrum. (FF: fill factor)

|                      | $J_{sc}$ [mA/cm$^2$] | $V_{oc}$ [V]  | FF [%]  | $R_d$ [Ω.cm$^2$] | $R_{SH}$ [Ω.cm$^2$] | PCE Average [%] | PCE Best [%] |
|----------------------|----------------------|----------------|---------|------------------|---------------------|-----------------|---------------|
| PTB7:PC_{71}BM       | 14.2 ± 0.22          | 0.708 ± 0.004  | 72.9 ±  0.64 | 0.99 ± 0.22     | 1477 ± 403          | 7.34 ± 0.14     | 7.58          |
| PTB7-Th:PC_{71}BM    | 15.7 ± 0.69          | 0.793 ± 0.009  | 64.9 ± 0.82 | 1.23 ± 0.23     | 899 ± 139           | 8.06 ± 0.36     | 8.66          |
| PTB7-Th:EH-IDTBR     | 15.4 ± 0.28          | 0.997 ± 0.004  | 55.3 ± 1.93 | 1.73 ± 0.32     | 576 ± 102           | 7.82 ± 0.27     | 8.79          |
Figure S3: J-V characteristics of the PTB7-Th:EH-IDTBR blend under fluorescent illumination intensity of 0.7 mW/cm²

Figure S4: Comparison of the (a) power conversion efficiency (PCE) and photovoltaic performance parameters (b) open circuit voltage ($V_{oc}$) and (c) fill factor (FF) of the best performing OPV blend of PTB7-Th:EH-IDTBR under different illumination of 1 Sun, white LED and compact fluorescent lamp (CFL).
Table S2: Photovoltaic performance parameters of the PTB7-Th:PC$_{71}$BM and PTB7-Th:EH-IDTBR solar cells as a function of indoor lighting condition.

| Light Source/Power | Light Source/Power | $J_{sc}$ [mA/cm$^2$] | $V_{oc}$ [V] | FF [%] | PCE [%] | Output Power [mW/cm$^2$] |
|-------------------|-------------------|----------------------|--------------|--------|---------|--------------------------|
| PTB7-Th:PC$_{71}$BM | White LED (5.9) | 1.32 | 0.731 | 66.3 | 10.9 | 0.64 |
| PTB7-Th:EH-IDTBR | White LED (5.9) | 1.43 | 0.974 | 59.4 | 14.1 | 0.83 |
| PTB7-Th:EH-IDTBR | CFL(0.7) | 0.183 | 0.898 | 57.6 | 13.6 | 0.095 |

Figure S5: (a) Transmitter laser diodes and receiver lens , (b) OPV holder (each can hold two panels).

Figure S6: Frequency responses of SISO setup for different OPV types.
Supplementary Note 1: Comparing OPVs with commercial solar cells

The external quantum efficiency spectra of commercial solar cells, such as silicon and GaAs [1, 2], are compared with our OPVs in Fig. S8. The emission spectra of the indoor light sources, i.e., white LED and fluorescent lamp, are also shown for comparison. Whilst all the materials in Fig. S8 absorb fluorescent or LED light effectively, OPVs have a wider bandgap than the inorganic semiconductors and hence smaller thermalization losses. It has been reported previously [3, Fig. 3] that amorphous (a-Si) and crystalline silicon (c-Si) solar cells show only a marginal increase in power conversion efficiency under indoor lighting conditions compared to OPVs as shown in Fig S3. Table S3 shows the comparison of the photovoltaic properties of the OPV blend in our study and the silicon solar cell for different illumination levels [4, 5].

Figure S7: Comparison of OPVs with commercial solar cells (data taken from [1,2]).

Figure S8: The PCE of the silicon solar cells compared to OPVs under 1 Sun and indoor lights (data taken from [3]).
|                        | Illumination   | \(J_{sc}\) [mA/cm\(^2\)] | \(V_{oc}\) [V] | FF [%] | PCE Avg [%] | PCE best [%] |
|------------------------|----------------|-----------------------------|----------------|------|-------------|--------------|
| PTB7-Th:EH-IDTBR       | 1 Sun 100 mW/cm\(^2\) | 15.4±0.3                    | 0.98±0.0       | 55.3±1.9 | 7.8±0.3     | 8.8          |
| PTB7-Th:EH-IDTBR       | Fluorescent 0.3 mW/cm\(^2\) | 0.09±0.0                    | 0.81±0.02      | 54.9±5.2 | 13.7±1.2    | 14.6         |
| c-Si                   | 1 Sun 100 mW/cm\(^2\) | 19.2                         | 0.52           | 70    | 7.0         |              |
| c-Si                   | Solar spectrum 0.1 mW/cm\(^2\) | 0.167                        | 0.15           | 40    | 1.0         |              |

Table S3: The comparison of the photovoltaic properties of the OPV blend in our study and the silicon solar cell for different illumination levels [4, 5].

**Supplementary Note 2: DCO-OFDM with adaptive bit loading**

Orthogonal frequency division multiplexing (OFDM) is a multicarrier modulation technique with a long history in wireless communication systems. OFDM has been commercialized and incorporated in the latest generations of radio frequency (RF) wireless communication and many standards, such as the IEEE 802.11 family used in Wi-Fi. OFDM elegantly addresses the issue of inter-symbol interference which is particularly severe in high data rate wireless systems. This is because of the unavoidable multipath propagation. The available system bandwidth is divided into a number of orthogonal subchannels of equal bandwidth. Data is modulated on these subchannels. Due to the relatively small bandwidth of a subchannel compared to the system bandwidth, the frequency response per subchannel is generally flat if a cyclic prefix is added to the time-domain OFDM symbol. The cyclic prefix should be at least as long as the maximum multipath delay. This means that a single tap equalizer can be deployed in the frequency domain to equalize the channel. As a result, intersymbol interference is effectively mitigated.

Among the advantages of VLC is the possibility of implementation using low-cost commercially available light sources. This is realized by modulating the output optical power of the light source (i.e., intensity of light) by changing its driving current. Therefore, the time domain signal should only contain real and positive samples. Single carrier modulation schemes such as pulse amplitude modulation (PAM) can be easily adopted for VLC. However, OFDM generally produces complex-valued bipolar time-domain samples, and thus, it must be modified to be applicable to VLC. This can be achieved by using a property of the Fourier transform. Specifically, by imposing the Hermitian symmetry on the signal in the frequency domain, the time domain signal would be real. Subsequently, a constant direct current (DC) bias is added to the signal so that the signal becomes mostly positive. However, depending on the value of the DC bias a few samples may still be negative which need to be clipped to zero before transmission. Taking into account the Hermitian symmetry and the DC bias, the frequency domain subcarrier vector, \(x\), is described as

\[
x = [0, x_1, \cdots, x_{n_s/2-1}, 0, x^*_n, x^*_n, \cdots, x^*_1],
\]

where \(n_s\) is the number of available subcarriers.

Each subcarrier is modulated by a \(M_k\)-ary quadrature amplitude modulation (\(M_k\)-QAM) symbol. The value of \(M_k\) depends on the available signal-to-noise ratio (SNR) at that subcarrier, \(\gamma_k\), to meet the bit error ratio (BER) constraint, \(4.7 \times 10^{-3}\) in this paper. This technique is referred to as the adaptive bit loading. The use of adaptive bit loading leads to the maximum achievable data rate [7]. The BER at the \(k\)th subcarrier is approximated as follows [8]:

\[
\text{BER}_k \approx 4 \left(1 - \frac{1}{\sqrt{M_k}}\right) \times \sum_{l=1}^{\min(2, \sqrt{M_k})} Q \left(\frac{1}{2} - \frac{1}{\sqrt{2M_k}}\right) - 3\gamma_k \left(2l - 1\right)^{-1/2}
\]

where \(Q(.)\) is the Gaussian Q-function. An algorithm is used for bit loading to determine the maximum \(M_k\) for \(k = 2, \cdots, n_s/2 - 1\). At each subcarrier, the BER\(_k\) is calculated for the available SNR, \(\gamma_k\), for values of \(M_k\) increasing from \(M_k = 2\). The maximum value of \(M_k\) is found so that the BER\(_k\) is still below the target.
The overall data rate is given by [9]:

$$\rho = \sum_{k=2}^{N_{s}} \frac{1}{2} \log_2 M_k \left( N_s + N_{CP} \right) / 2B,$$  \hspace{1cm} (3)

where $B$ is the single-sided system bandwidth, and $N_{CP}$ is the cyclic prefix size.

**Supplementary Note 3: OPV model**

A solar cell can be modeled by the circuit shown in Fig. S9 for simultaneous energy harvesting and communication analysis [6]. The photo-current source contains both the DC component $I_{PH}$ and the AC component $i_{PH}$. The resistor $r$ represents the small signal equivalent of the solar cell diode in the DC model. A capacitor $C$ is used in parallel with $R_{SH}$ to model the internal capacitance of the solar panel. An inductor $L$ is set in series with $R_s$ to model the inductance of wire connections within the solar panel. The output of the solar panel is connected to two branches: the communication branch and the energy harvesting branch. In the communication branch, a capacitor $C_0$ is connected to the output of the solar panel to block the DC signal and to pass the AC signal. The energy harvesting branch includes an AC signal filtering inductor $L_0$ and a load resistor $R_L$. The electrical power gain of the circuit can be determined as follows [6]:

$$\left| \frac{v(\omega)}{i_{PH}(\omega)} \right|^2 = \left| \frac{R_{LC}}{R_s + j\omega L + R_{LC}} \frac{R_C}{j\omega C + R_C} \right|^2$$  \hspace{1cm} (4)

where $\omega = 2\pi f$ is the angular frequency, $j = \sqrt{-1}$ and $R_{LC}$ is the equivalent resistance of the two parallel branches and is calculated as follows:

$$R_{LC} = \frac{1}{\frac{1}{j\omega L_0} + \frac{1}{R_L} \frac{1}{j\omega C} + \frac{1}{R_C}}$$  \hspace{1cm} (5)

![Solar panel model for simultaneous energy harvesting and data communication.](image)

**Supplementary Note 4: Electrical gain coefficient calculation**

The electrical gain values can be derived from the RLC circuit which is formed by connecting multiple circuits shown in Fig. S9. For instance, as shown in Fig. S10 for a 2-by-2 MIMO system, each OPV cell requires a RC circuit for signal extraction while all OPVs are connected in series with a single RL circuit for energy harvesting. Considering a setup with $N_{cell}$ OPV cells being connected in series, the elements of the electrical channel gain matrix, $G^{N_s \times N_c} = [g_{nm}]^{N_s \times N_c}$, at the main diagonal are expressed as:

$$g_{(n=m)} = \frac{\left( N_{cell} - 1 \right) R_s + R_{1,L}}{\left( N_{cell} - 1 \right) R_s + R_{1,L} + R_{1,c}} \times \frac{R_0}{R_{1,s} + \left( \left( N_{cell} - 1 \right) R_s + R_{1,L} \right) / R_{1,c} + R_0 \times R_c},$$  \hspace{1cm} (6)
The nondiagonal elements, i.e., the crosstalk gains, are nonzero and are expressed as:

\[ g_{nm} = \frac{R_0 + R_{1,s}}{R_{1,e} + R_0 + R_{1,s}} \times \frac{R_{1,c}}{(N_{\text{cell}} - 1)R_x + R_{1,L} + R_{1,c}} \times \frac{R_0}{R_{1,s} + ((N_{\text{cell}} - 1)R_x + R_{1,L})/R_{1,c} + R_0} \times R_c, \]

where // denotes connected in parallel, and: \( R_{1,L} = R_L + j\omega L_0 \), \( R_{1,e} = R_C + \frac{1}{j\omega C_0} \), \( R_{1,s} = R_s + j\omega L \), \( R_0 = R_{\text{SH}}/\left(\frac{1}{j\omega C_0}\right) \), and \( R_x = (R_0 + R_{1,s})/R_{1,c} \).

Figure S10: Solar panel model for simultaneous energy harvesting and data communication for a 2-by-2 MIMO system. \( h_{mn} \) denotes the optical channel gain from the \( n^\text{th} \) transmitter to the \( n^\text{th} \) receiver. \( v_1(\omega) \) and \( v_2(\omega) \) represent extracted AC signals for the two data streams. Laser diode (LD).

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