Northumbria University
NEWCASTLE

Data Rate Enhancement using an Artificial Neural Network Equaliser in Optical Camera Communications

Othman Younus[1], N. B. Hassan[1], Z. Ghassemlooy[1], P. A. Haigh[2], S. Zvanovec[3], L. N. Alves[4], and H. Le Minh[1]

1. Optical Communications Research Group, Faculty of Engineering and Environment, Northumbria University, Newcastle upon Tyne, UK. **2.** Intelligent Sensing and Communications Group, School of Engineering, Newcastle University, U.K.

3. Department of Electromagnetic Field, Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic. **4.** Department of Electronics Telecommunications and Informatics, Instituto de elecomunicações, University of Aveiro, Aveiro, Portugal.

Objectives

A novel artificial neural network (ANN)-based equaliser with an adaptive algorithm is presented to mitigate inter-symbol interference (ISI) and therefore increase the data rate. The proposed system is theoretically investigated and experimentally evaluated. The results show bandwidth improvement of 2 to 9 times depending on the camera's exposure time where the system's bit error rate is below the forward error correction limit.

Introduction

Optical wireless communications (OWC) has attracted growing research interest in recent years due to its many desirable properties [1] .

- Large available spectrum (350 nm to 1550 nm)
- High energy-efficiency
- Independent regulation
- Inherent security.

Current research in OWC is focused on:

- Free space optical (FSO) communications
- Visible light communications (VLC) (i.e., Li-Fi)
- **Optical camera communications (OCC)**
- Indoor GPS.

OCC systems leverage on the use of commercial off-the-shelf image sensors (IS), i.e., cameras, to perceive the spatial and temporal variation of light intensity to enable data transmission.

OCC - Benefits

- A range of divers applications [2].
- Offer massive MIMO – A typical IS is composed of very large number of pixels, which provide a large degrees of freedom (DoFs) to transmit data and to handle the access of a massive number of users.
- Parallel transmission detection capability - The image sensor can deal with three colours.

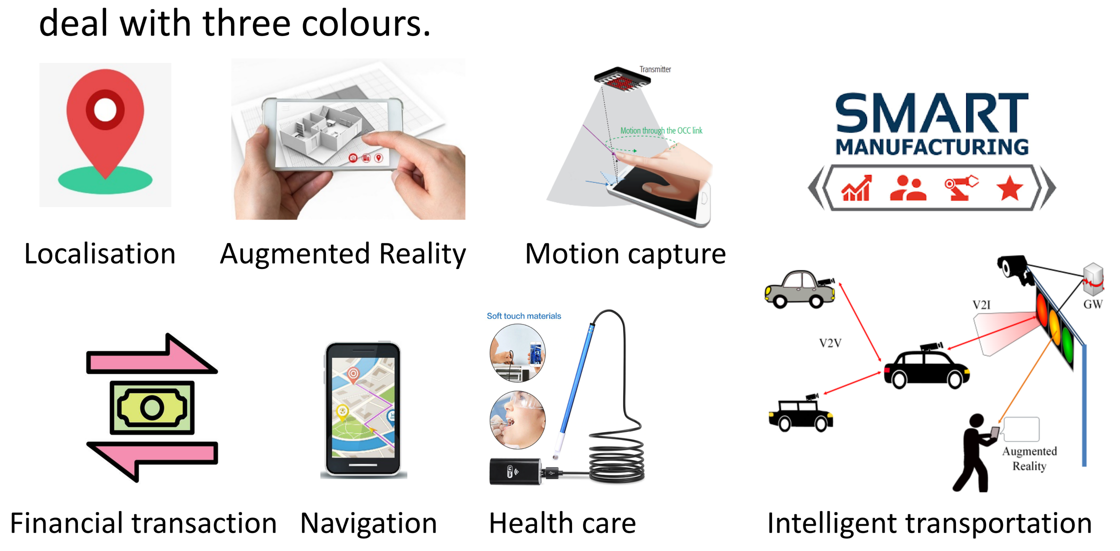
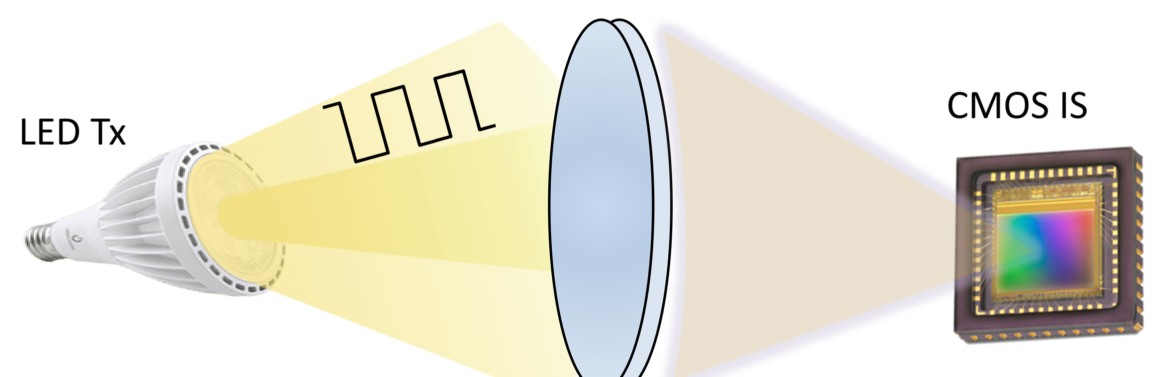


Fig. 1. OCC potential applications.

OCC - Challenges

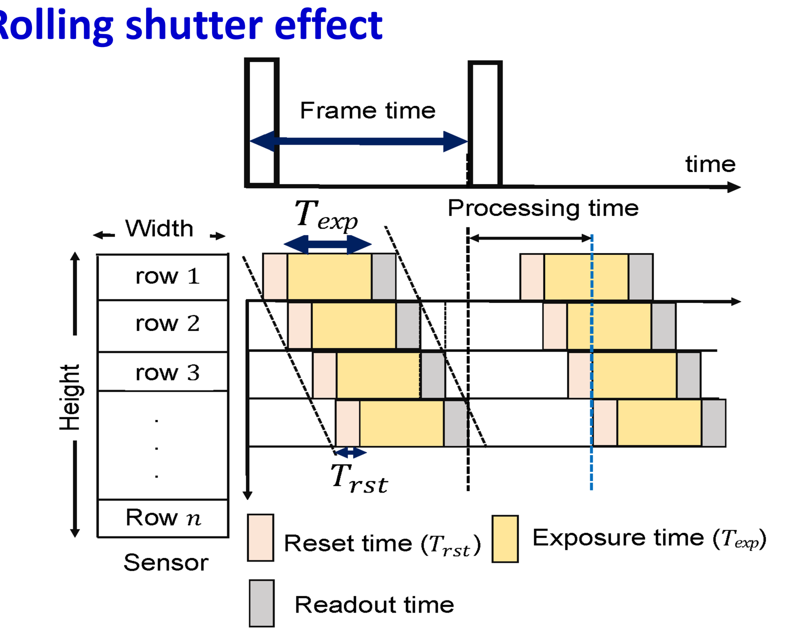


- Out-of-focus effect
- Random blocks
- Limited low data rates due to low sampling rate at the Rx
- Unstable frame rates

Fig. 2. Current challenges in OCC systems [2-3] .

OCC - CMOS Modelling

Rolling shutter effect



An array of pixels is used to capture the incident light in a progressive manner.

Fig. 3. An example of the frame acquisition based on rolling-shutter CMOS sensor.

- The incident light at high frequencies and relatively low exposure times T_{exp} is observed by forming different illuminated bands.
- The standard IS-based receiver (Rx) is modelled as a linear shift-invariant (LSI) system. The voltage corresponds to an individual photodiode is given by [4]:

$$v_r(t) = \frac{A}{C_{PD}} \int_{t-T_{exp}}^{t} \Re . x(t)dt, \quad (1)$$

- where A is the gain, C_{PD} and $\Re$ are the equivalent capacitance and responsivity of the PD, respectively and $x(t)$ is the received optical signal at the pixel (U, V) at time t.

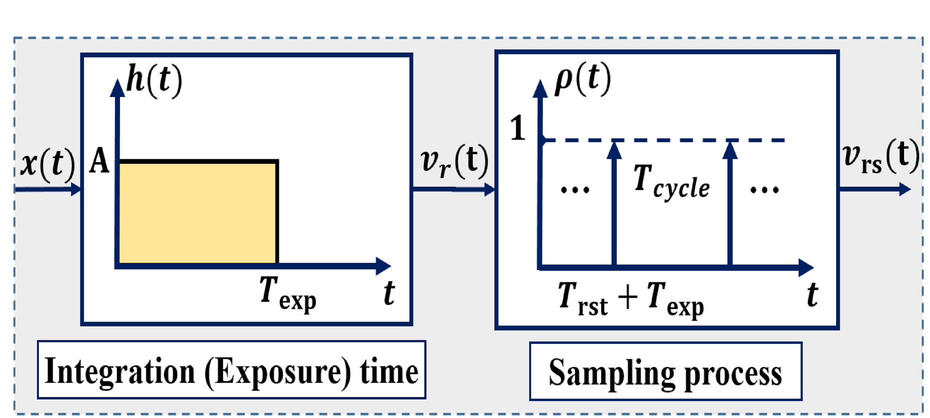
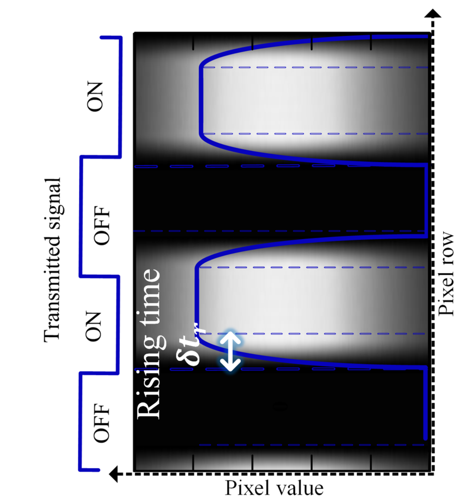


Fig. 4. The LSI model of a CMOS image sensor receiver.

- The system response represents an integration of the input signal over T_{exp} which results in the low-pass filter effect with a transfer function given as [4]:

$$H(f) = \mathcal{F}\{h(t)\} = \frac{A\,T_{exp}}{C_{PD}} \frac{\sin(\pi f T_{exp})}{\pi f T_{exp}} e^{-j\pi f T_{exp}}. \quad (2)$$

- The DC gain is proportional to T_{exp}, therefore a trade-off between the gain and the required bandwidth, where increasing T_{exp} will reduce the cut-off frequency.
- The bandwidth limitation imposed by the sampling process of IS (i.e., LPF) results in ISI at higher data rates, thus leading to a significant degradation in system performance.



The slow rise-time of the detected symbol (i.e., OOK data stream) by the camera is affected by the existence of the transition between different illumination levels.

Fig. 5. An example of the frame acquisition based on RS CMOS sensor.

Artificial Neural Network Equaliser

Equalisation

- **In the information theory:** ISI is predicted by training filter coefficients based on a training sequence in order to minimise the error cost.
- **In classification:** Class decision boundaries are created in order to classify symbols based on training.

- Classification allows generalisation because of the use of boundaries, where unknown symbol transitions can be tolerated.
- Linear decision boundaries are not sufficient to provide an optimal decision in practical channels, where the threshold boundaries are nonlinear.
- **ANN-based equalisers** with realisation of nonlinear decision boundaries offers improved performance in communication systems [4].
- **ANNs-based equaliser** deployed in a fully connected mode have been shown to offer superior performance in photodetector-based communication links.
- Here, **an ANN-based equaliser for OCC is proposed and implemented** for the first time in order to increase the transmission data rates by mitigating the ISI induced by high sampling duration.

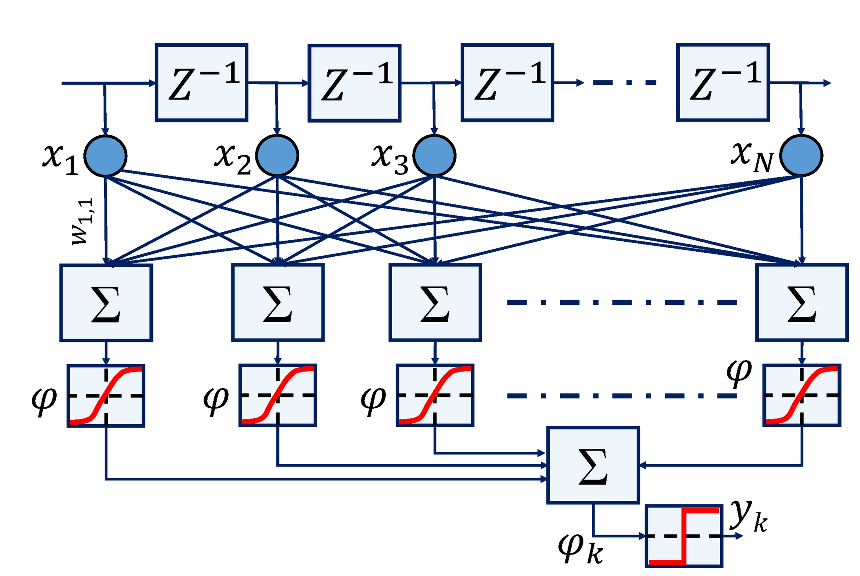


Fig. 6. Block diagram of a single-hidden-layer ANN based equaliser

OCC with ANN Equaliser - Proposed Model

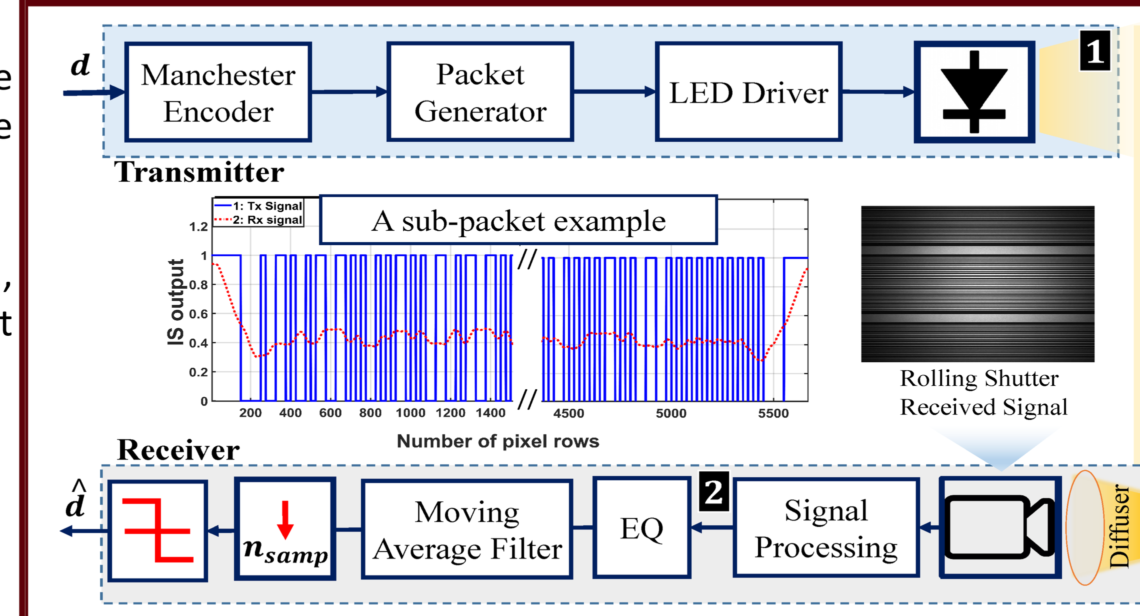


Fig. 7. System block diagram for OCC using LED and rolling shutter CMOS sensor.

Results

- We experimentally demonstrated an OCC system using an ANN adaptive equaliser at the Rx to study for the first time its performance.
- The data rates achieved were recorded as 12 kbps at the exposure time of 2, 1, and 0.5 ms, see Fig. 8, using a single source and the MLCNRZ encoded signal, which are sufficient for many applications.
- The proposed system demonstrated the capability in retrieving the transmitted information with a bandwidth beyond the cut-off frequency limitation. Hence, it offered **bandwidth improvement of around 9, 5, and 2 times at the exposure times of 2, 1, and 0.5 ms,** respectively.

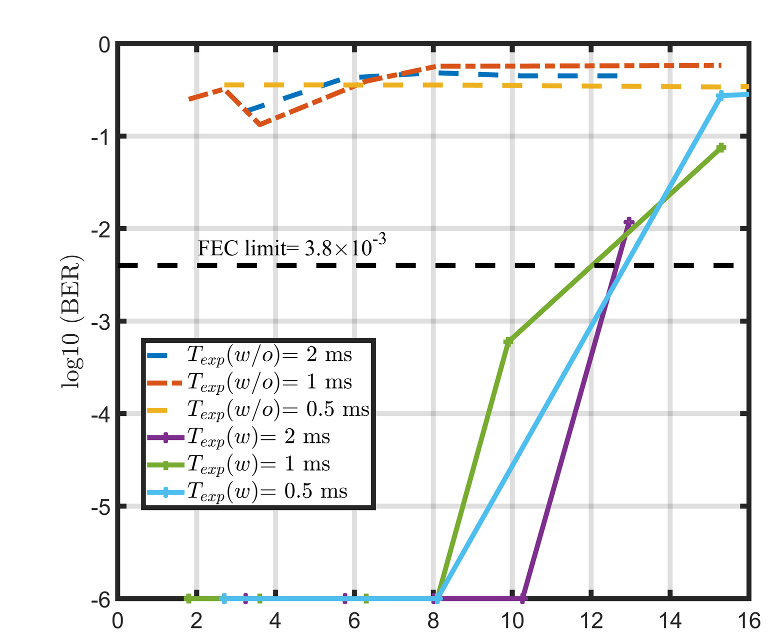


Fig. 8. BER measurements of the system with and without equalisation in respect to effective data rates of different exposure times with *Rf* of 30.

Future Research

Investigating different modulation schemes with the proposed equaliser to further increase the transmission data rate and improve the link performance.

References

[1] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical wireless communications: system and channel modelling with Matlab®*. CRC press, 2019.
[2] P. A. Haigh *et al.*, "A MIMO-ANN system for increasing data rates in organic visible light communications systems," in *2013 IEEE International Conference on Communications (ICC)*, 2013, pp. 5322-5327.
[3] H. Chen *et al.*, "Color-Shift Keying for Optical Camera Communication Using a Rolling Shutter Mode," *IEEE Photonics Journal,* vol. 11, no. 2, pp. 1-8, 2019.
[4] N. Saeed, S. Guo, K.-H. Park, T. Y. Al-Naffouri, and M.-S. Alouini, "Optical Camera Communications: Survey, Use Cases, Challenges, and Future Trends," *eprint arXiv:1812.01259,* p. arXiv:1812.01259, 2018.

Acknowledgements

- Northumbria University for the PhD scholarship
- IEEE ComSoc UK and Ireland Section