DCO-OFDM Channel Sounding with a SiPM Receiver

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***Abstract*— Orthogonal Frequency-Division Multiplexing (OFDM) is a popular modulation scheme, which requires a linear channel. Unfortunately, the most sensitive receivers for visible light communications, silicon photomultipliers (SiPMs), have a non-linear response. Despite this incompatibility, results from an easily implemented method of combining OFDM and SiPMs are shown to successfully limit the bit error rate to below the limit required by forward error correction.**

Keywords—Silicon Photomultiplier (SiPM), Visible Light Communications (VLC), Optical Wireless Communications (OWC)

I. Introduction

Visible light communications (VLC) is being developed to augment in-door Wi-Fi infrastructure. A key component of any VLC system is the receiver and recently experiments have been performed with receivers that incorporate silicon photomultipliers (SiPMs) that can detect individual photons. However, with few exceptions these experiments have been performed using on-off keying (OOK) [1]. Another modulation scheme that is often used in VLC systems is Orthogonal Frequency-Division Multiplexing (OFDM) [2]. By using adaptive data and power allocation to multiple frequency sub-carriers, this modulation scheme can exploit a VLC channel's bandwidth. However, the required orthogonality between frequency sub-carriers, is only achieved if the VLC channel is linear. The linearity of the channel also simplifies the process used to assign the maximum number of bits and the minimum power needed to achieve the target bit error rate (BER) to each frequency sub-carrier. In contrast, the mechanism used within SiPMs to detect individual photons means that they have a non-linear response to changes in irradiance. Consequently, there are only a few reports of results obtained using OFDM with a SiPM and the highest data rate that has been achieved is 20 Mbps [3].

In this paper, the impact of SiPM non-linearity on OFDM is reported and a simple method of assigning bits to each frequency sub-carrier is described. The result is an easily implemented, reliable method of transmitting OFDM signals over a non-linear channel.

II. SiPM Saturation

The SiPM used for this investigation was an ON Semiconductor J-30020 SiPM on a SMPTA evaluation board. This SiPM has 14,410 microcells that share a common output line. Each microcell contains a single photon avalanche photodiode (SPAD) in series with a quenching device. These microcells are biased above their breakdown voltage so that a photon can initiate an avalanche process, which is quenched when the voltage across the SPAD is reduced by the current flowing through the quenching device. This means that after each photon is detected the capacitance of a microcell must be recharged by the voltage source used to bias the microcells. The current flowing from this voltage source therefore depends upon the rate at which photons are detected.

Fig. 1 (a) shows the current supplied by the source of the 28 V bias voltage as the irradiance falling on the SiPM from a 405 nm laser diode was varied. The results in this figure show that the expected linear region extends up to an irradiance of 10 mWm^{-2}. At higher irradiances, the relationship between bias current and irradiance becomes non-linear.

III. Channel Sounding Performance

For data transmission experiments, DCO-OFDM data were generated in MATLAB® and supplied to a Tektronix 70002AE arbitrary waveform generator (AWG) with a maximum output of 250 mV_{pp}. This RF signal was then fed via a 6 dB attenuator (VAT-4W2+) to a Fairview FMAM3269 36 dB gain, 10 MHz-6 GHz amplifier. The resulting 1.4 Vpp signal was then added to a d.c. voltage by a Mini Circuits ZFBT29W Bias Tee before it was applied to a ThorLabs L405P150 laser diode. The resulted 405 nm modulated laser light then passes through a polariser, which was used to vary the transmitters output power. After the polariser, the beam was coupled into an optical fibre which illuminated the back of a ground glass diffuser approximately 50 cm above the SiPM receiver. In some experiments a ThorLabs neutral density filter was placed after the diffuser to obtain irradiances at the receiver below 10 mWm^{-2}. The receiver in these experiments was the J-30020 SiPM on a SMTPA evaluation board. The anode of this SiPM was connected directly to ground and its fast output was connected via a Mini-Circuits ZX60-14012L-S+ 300 kHz-14 GHz amplifier to a Keysight MSOV334A 33GHz oscilloscope. After each experiment the irradiance falling on the SiPM was measured using an 818-UV calibrated photodiode.

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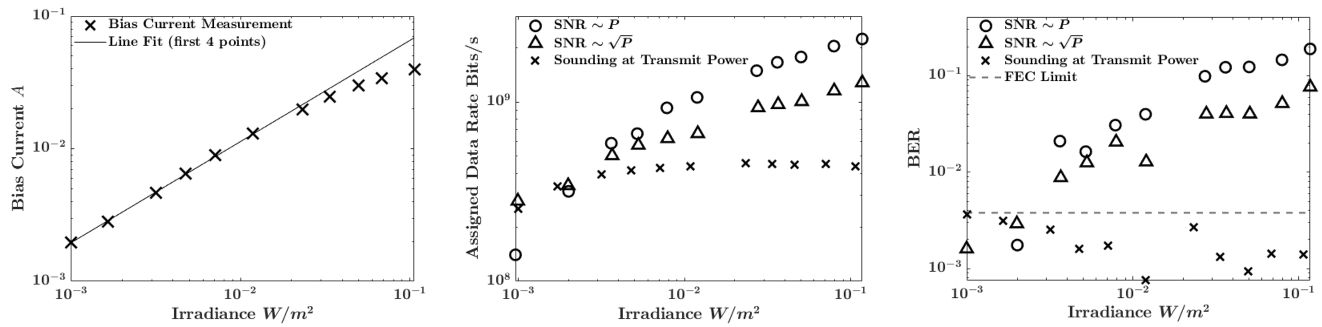

(a) (b) (c)

Fig 1 (a) Shows the current needed to sustain the bias voltage across the microcells in the SiPM at different irradiances from the 405 nm laser diode. (b) shows the OFDM data rate at various irradiances for three different methods of sounding the VLC channel and assigning bits and power to each sub-carrier. (c) shows the bit error rate achieved at the data rates from (b) for the same three methods.

The transmitted DCO-OFDM was clipped to limit both its minimum and maximum values. A d.c. bias of 6 dB, which corresponds to 1.7 standard deviations of the unclipped OFDM signal was then added to the signal. A signal was sampling at 750 MHz and 1024 subcarriers were utilised with a cyclic prefix length of 32. The result was a symbol time of 1.4 µs, which is approximately 100 times longer than the time needed to recharge the SiPM's microcells. The received waveform was low pass filtered, demodulated, and equalized using a one-tap equaliser before the BER was calculated.

The channel was sounded with a QPSK constellation on every sub-carrier and at an irradiance on the SiPM of 2 mWm^{-2}, which is within the linear region in Figure 1 (a). The measured SNR per sub-carrier, waterfilling and the Shannon capacity limit were then used to perform bit loading and determine the power of each sub-carrier [4]. Initially, this process was performed using one of two assumptions. The first assumption was that the noise in a sub-carrier is independent of the power assigned to the sub-carrier. Consequently, the SNR of the sub-carrier is proportional to the power assigned to the sub-carrier. However, this usual assumption doesn't take into account the SiPM's ability to detect individual photons, which means that their dominant noise source is expected to be shot-noise [5]. This noise source means that the SNR is expected to be proportional to the square root of the power assigned to the sub-carrier. Fig. 1 (b) shows the data rates at different irradiances calculated using these two assumptions. More importantly, Fig. 1(c) shows the bit error rate (BER) measured at each of these data rates. These results show that using these assumptions results in BERs above the limit of 3.8×10^{-3} required to achieve an acceptable final BER after forward error correction (FEC). These results also show that the SiPMs non-linear response has an impact on OFDM at irradiances significantly lower than the irradiances at which the response appears to be non-linear in Fig. 1 (a).

Any non-linear response creates harmonics of each input sine wave. To take account of the impact of this effect on the SNR of each sub-carrier the channel was sounded at the irradiance that was also used to transmit data. The results in Fig. 1 (b) shows that this easily implemented method leads to lower data rates. However, critically, the results in Fig. 1 (c) show that using this method limits the BER at all data rates to less than the limit required by FEC. In addition, the maximum data-rate achieved using this method was 453 Mbps.

IV. Conclusion

SiPMs can detect individual photons, however, the mechanism used to detect each photon creates a non-linearity in the response of SiPMs to varying irradiances. Because OFDM assumes a linear channel, this non-linearity is particularly important when OFDM is the chosen modulation scheme. Results have been presented which show that this non-linearity means that conventional methods of loading the OFDM sub-carriers fail at irradiances much lower than those expected from the SiPM's non-linear response. More importantly, an easily implemented and reliable method of loading the OFDM sub-carriers has been described and used to achieve a data rate of 453 Mbps.

References

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