A Study of Discrete Wavelet Transform Based Denoising to Reduce the Effect of Artificial Light Interferences for Indoor Optical Wireless Communication

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***Abstract*—The optical power penalty (OPP) due to the artificial light interferences (ALIs) can be significantly high in an indoor optical wireless communication (OWC) channel making such link practically infeasible. A discrete wavelet transform (DWT) is an effective technique in reducing the ALI effects. The DWT has the advantage over the high pass filtering (HPF) to reduce ALI in terms of complexity and performance. In this paper, a comprehensive study of the DWT based denoising for the on-off keying (OOK), pulse position modulation (PPM) and digital pulse interval modulation (DPIM) is provided. The OPPs due to ALIs and DWT based denoising for these modulation techniques are presented.**

I. INTRODUCTION

The invention of optical fibres, semiconductor devices and laser diodes had offered a wide bandwidth that were more than adequate in 60s till 90s, when the communications were dominated by the audio-video broadcasting. However, the recent explosive growth in the bandwidth demand for personal communications mainly due to the rapid growth in computer speed and internet technology had quickly changed the scenario. Though the long haul communications are keeping pace with the excessive bandwidth demand, the local loop bottleneck is becoming an acute problem. The bottleneck can largely be attributed to the copper cable connection in the last mile. However, alternative technology in the form of an OWC is already available to address the problem [1, 2].

OWC offers licence free availability of an unlimited bandwidth in infrared (IR) and a visible spectrums. OWC systems also offer fast deployment, secure communication and cheap transceivers. The outdoor OWC suffer from a number of adverse environmental conditions like temperature and pressure fluctuation, fog, rain and smoke. Due to relatively short link length, the indoor OWC systems are free from the adverse environmental effect. However, a different type of challenge occurs in indoor environment. The high blocking probability due to objects, multipath induced intersymbol interference (ISI) and power limitation due to the eye safety are the key limitations in the indoor environment. In this study, a technique to reduce ALI effect in indoor OWC links is investigated by means of employing the DWT denoising.

ALI has a periodic nature with frequency components ranging from a DC level up to few MHzs [3-5]. ALI produced by the fluorescent lights is the most dominating source of interference and can result in a very high OPP. A number of techniques have been proposed to reduce the effect of ALI, more recently DWT based denoising [6]. DWT offers a clear advantage over the digital HPF in terms of performance as well as complexity. Our previous papers reported the performances of the OOK and the DPIM schemes [6, 7]. This paper provides a comprehensive study of DWT based denoising for OOK, PPM and DPIM modulation schemes and shows the effectiveness of the DWT to reduce the ALI.

The paper is organised as follows: a brief overview of baseband modulation techniques are given in Section II followed by the concept of DWT based denoising in Section III. The normalized optical power requirement (NOPR) to achieve an error probability of 10^{-6} in the presence of fluorescent light interference (FLI) with and without denoising for OOK, PPM and DPIM schemes is given in Section IV. Finally, conclusions are drawn on Section V.

II. OVERVIEW OF BASEBAND MODULATION TECHNIQUES

A number of baseband signalling schemes for indoor OWC systems exist in the literature. Fundamentally the binary data sequences are modified to achieve either a higher throughput or power efficiency. The simplest among the baseband modulations is the OOK in which the output of a modulator is a pulse or an empty slot of one slot duration according to the input binary data being ‘1’ or ‘0’, respectively. The input binary symbols are modified to limit the number of pulse per symbol to one in PPM so that the average transmitted optical power is significantly lower than that of the OOK scheme. In fact, PPM offers the unparallel power efficiency among the baseband modulation schemes. Further improvement in the throughput without significantly losing the power efficiency can be achieved by removing the redundant slots within a PPM symbol. The DPIM is a variable symbol length modulation technique derived by removing the empty slot after a pulse in PPM [8]. The DPIM can achieve higher power efficiency compared to the PPM by increasing the bit resolution. The detailed comparison of

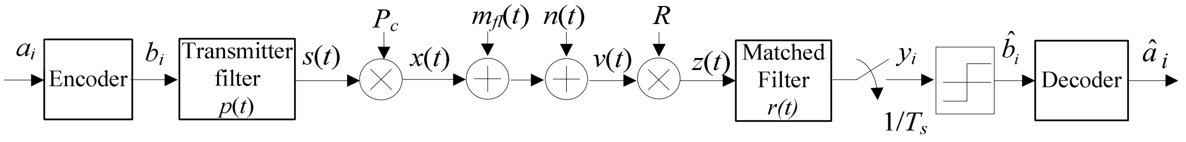


Figure 1: The block diagram of a generalized OWC system.

modulation techniques is beyond the scope of this paper and interested reader can refer to [8-11] and reference therein.

The system block diagram of a generalised OWC system with a matched filter based receiver is given in Fig. 1. The input data stream is converted into the required modulation format (OOK, PPM, DPIM or other) using an encoder. The encoder output is passed through a transmitter filter $p(t)$ with a unit-amplitude impulse response of one slot duration T_s to convert it to a continuous signal $s(t)$. The output of transmitter filter is scaled by a peak transmitted power P_c to achieve the required average optical power. Hence, the transmitted signal $x(t)$ can be represented as:

$$x(t) = P_c \sum_{i=-\infty}^{\infty} b_i \, p(t - iT_s). \tag{1}$$

where $b_i \in \{0, 1\}$; $i = 1,2 \ldots$ is the binary sequence from the encoder.

In addition to the additive white Gaussian noise (AWGN) $n(t)$, the indoor OWC channel also suffers from non-Gaussian periodic noise from artificial light sources. The interference produced by fluorescent lamps driven by electronic ballasts $m_{fl}(t)$ poses the most severe problem and can be modelled using a high frequency $m_{high}(t)$ and a low frequency $m_{low}(t)$ components of the photocurrent at the receiver [4, 5].The receiver consists of a photodetector with a reponsivity of R followed by a matched filter $r(t)$ and a sampler. The sampling rate depends on the slot duration, which depends on the data rate and bit resolutions. The output of sampler is sliced to generate a binary '1' or '0' followed by a decoder to covert the binary sequence to the original data format. The output of the matched filter due to the FLI signal, sampled at the end of each bit period, is given as [4]:

$$m_k = m_{fl}(t) \otimes r(t)\big|_{t=kT_s}. \tag{2}$$

The error probabilities for the matched filter based receiver for OOK, PPM and DPIM in the presence of AWGN are given in [9-11]. Since ALI is periodic in nature, the error probabilities can be estimated by calculating the error probability over a period of interference and averaging over the periods [4, 12]. To achieve a bit error rate (BER) of 10^{-6}, the NOPR is ~ 16.6 dB irrespective of the data rate for the OOK system. For the PPM and DPIM schemes, NOPRs depend on the bit resolutions and are discussed in section IV.

III. DWT BASED DENOISING

It is shown in the previous publications [6, 7] that the DWT has the potential to surmount the performance of a digital HPF with significantly reduced complexity. The DWT, in fact, is simpler to realize due to a highly repetitive structure. In this study, the generalized DWT based receiver for the OOK, PPM and DPIM is studied. The receiver structure based on the DWT is shown in Fig. 2. The wavelet denoising consists of a DWT decomposition module, a processing module for denoising and an inverse DWT module for reconstruction of the original signal. DWT decomposition involves splitting the signal $y(n)$ into lowpass $h(n)$ and highpass $g(n)$ signals as given by [13]:

$$y_{1h}(k) = \sum_{n} y(n)\, g(2k - n)\,; \tag{3}$$

$$y_{1l}(k) = \sum_{n} y(n)\, h(2k - n)\ . \tag{4}$$

The approximation coefficients y_{1l} can further be decomposed into different DWT coefficient levels if necessary. For the removal of the interfering signal from the received signal, the approximation coefficients which correspond to the interfering signal are made equal to zero so that the reconstructed signal is free from the interfering signal [6] i.e.

$$y_{\gamma l}(k) = 0. \tag{5}$$

where γ is the number of the decomposition levels. The signal is then reconstructed using the inverse of the decomposition process.

The number of decomposition level γ in this study is calculated using:

$$\gamma = -\lfloor \log_2(T_s \times F_c) \rfloor\,; \tag{6}$$

where $\lfloor . \rfloor$ is the floor function and F_c is the desired cut-off frequency. Hence, the number of decomposition level depends upon the required cut-off frequency and data rate (or slot rate).

The power spectral densities (PSDs) of the OOK signals at data rates of 2 and 200 Mbps corrupted by FLI and their denoised version using the DWT are shown in Fig. 3. The computer simulation is carried out to generate the PSDs using the model of photocurrent due to the

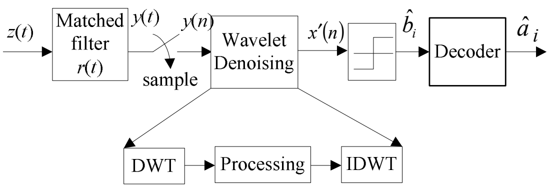
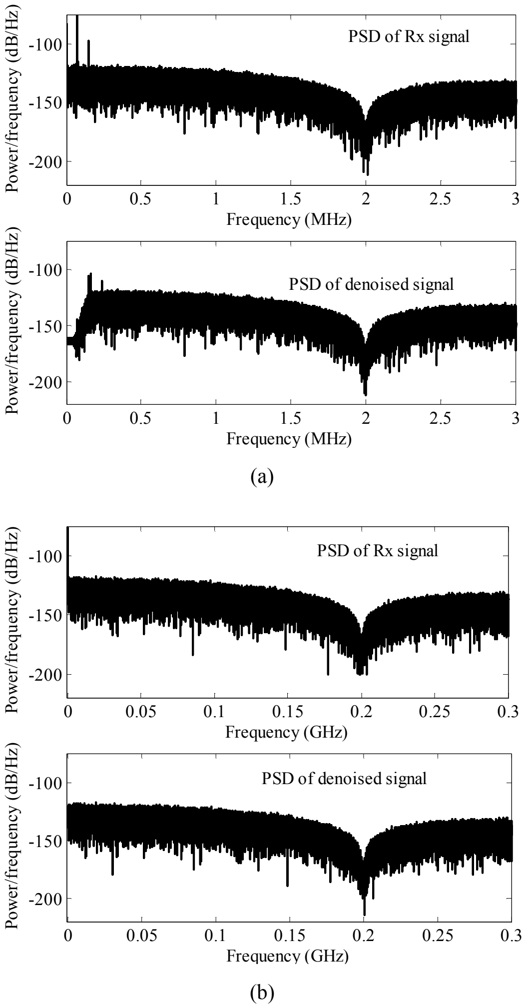


Figure 2: The DWT based receiver for the OWC system in presence of ALI.



(a)

(b)

Figure 3: The PSDs of received and denoised OOK signal at data rates of (a) 2 Mbps, and (b) 200 Mbps.

fluorescent lamps $m_{fl}(t)$ as given in [4, 5]. The Daubechies wavelet (db8) is used for the analysis with 6 levels of decompositions and the photocurrent due to interference is arbitrarily made four times that of the signal. For clarity, the received signal is assumed to be free from the AWGN as the focus is on the effect of FLI. The PSD of the denoised signal at 2 Mbps shows that there are no significant changes at frequencies > 0.5 MHz compared to the PSD of the received signal. A significant portion of the spectral content at < 0.3 MHz is removed (the approximated cut-off frequency is 0.31 MHz) with no DC contents. Because of the spectral overlap between the signal and interference (both having high DC and low frequency components), it is not possible to remove the interference without losing a significant portion of the signal, thus leading to increased power penalties. Hence, the task here is to make the power penalty as low as possible. Unlike the 2 Mbps case, there is not much change in the PSD of the received and the denoised signals on a large scale at 200 Mbps. However, at a closer look there is a significant change in PSD at < 0.3 MHz. Hence a significant amount of information is retained even with the wavelet denoising and it is expected that the power penalty would not be as high as at that of 2 Mbps case. With this observation, one can conclude that the signal with a low PSD at or near the DC region can provide an enhanced immunity to the FLI. The comparative studies of different modulation schemes having different DC levels are given below.

IV. RESULTS AND DISCUSSIONS

For the comparisons of different modulation schemes under different channel conditions, the OPP and NOPR are considered here. Let the desired (bit or slot) error probability for the system be ξ, OPP and NOPR are defined as:

a) NOPR: The NOPR of a system is calculated by normalising the optical power required to achieve the error probability of ξ in the interfering channel with that of OOK system at 1 Mbps in an ideal AWGN channel without interference, as defined in (7).

b) OPP: The OPP of a system is calculated by normalising the optical power required to the achieve the error probability of ξ in the interfering channel with that of ideal AWGN channel without interference (other system parameters like the modulation type, bit rate remains the same), as defined in (8).

For the comparative studies of the performance of the OWC system with and without DWT based denoising, the systems are simulated in Matlab and NOPR to achieve a BER of 10^{-6} is calculated under three different conditions: (a) channel without interference (b) channel with interference and (c) channel with interference and with DWT denoising. The channel is assumed to be a line of sight (LOS) with the AWGN. The simulation results are presented below.

A. OOK

The NOPRs for the OOK scheme under the constraint of the interference in the presence of the FLI is shown in Fig. 4. Since no performance improvement can be achieved below data rates of 10 Mbps, such rates are not considered here. The OOK scheme is very susceptible to baseline wander (BLW), hence only low normalized cut-off frequencies (normalized to sampling rate) are possible, which are not effective in reducing the interference at low

$$\text{NOPR} = \frac{\text{Optical power required to acheive } \xi}{\text{Optical power required to achieve } \xi \text{ for OOK @1 Mbps in ideal chhanel}}. \tag{7}$$

$$\text{OPP} = \frac{\text{Optical power required to acheive } \xi}{\text{Optical power require to achieved } \xi \text{ in an ideal AWGN channel}}. \tag{8}$$

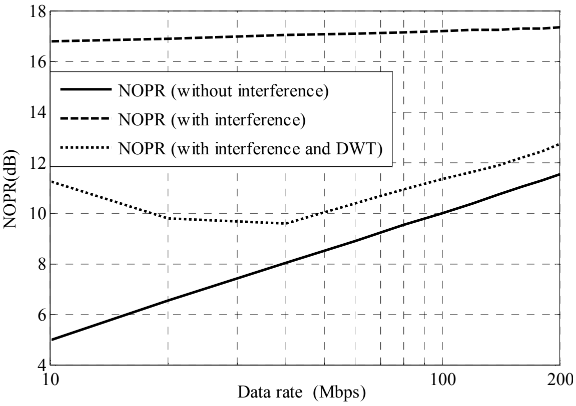


Figure 4: The NOPR against the data rates for the OOK modulation scheme with and without the DWT denoising in the presence of FLI.

data rate. At data rates above 10 Mbps, the DWT is very effective in reducing the interference. The DWT offer a reduction of ~ 5.5 dB and ~ 7.4 dB in NOPRs compared to the system without filtering at data rates of 10 Mbps and 40 Mbps, respectively. This leaves OPPs of ~ 6.3 dB and ~ 1.6 dB compared to the ideal case. Lower OPPs are observed at higher data rates and the OPP of ~ 1.2 dB is observed at 200 Mbps.

B. PPM

The PPM with a soft decision decoding offers a significant resistance to FLI at data rates > 20 Mbps. Hence, in this study, the soft decoding with DWT denoising is considered only for data rate of < 20 Mbps. However, a high OPP occurs for PPM with a hard decision decoding scheme and with no denoising. The receiver structure given in Fig. 2 is used for the DWT with the decomposition level given by (6). The desired cut-off frequency F_c is taken as 0.5 MHz except for a data rate of 1 Mbps ($F_c = 0.3$ MHz is utilized at 1 Mbps). For the hard decision decoding, the threshold level α is set midway between one and zero levels in the absence of any BLW, given as [8, 14]:

$$\alpha = RP_{avg}\sqrt{LT_b \log_2 L}\,\left(\frac{1}{2}-\frac{1}{L}\right). \qquad (9)$$

The NOPR to achieve an error probability of 10^{-6} with the DWT denoising for 4, 8 and 16-PPM with the hard decision decoding scheme for data rates of 1-200 Mbps is demonstrated in Fig. 5. Unlike OOK, the DWT offers significant reduction in NOPRs even at low data rates (~10.7 dB, ~12 dB and ~12.2 dB for 4, 8 and 16 PPM, respectively at a data rate of 1 Mbps). Since the PPM scheme has no DC component and low spectral components at low frequency region, a higher cut-off frequency can be tolerated without BLW effect. Hence, DWT offers improvement even at low frequencies for the PPM scheme. Above a data rate of 10 Mbps for 4-PPM and 5 Mbps for the 8 and 16-PPM, the DWT based denoising completely eliminates OPPs due to FLI.

The NOPR to achieve an error probability of 10^{-6} with DWT denoising for 4, 8 and 16-PPM with the soft decision decoding scheme for a data rate range of 1-200 Mbps is given in Fig. 6. The DWT offers no improvement above a data rate of 20 Mbps as the PPM with the soft decoding is immune to the FLI. The DWT provides a significant improvement even at 1 Mbps with OPPs of ~ 4 dB, ~ 2.9 dB and ~ 1 dB for 4, 8 and 16 PPM, respectively compared to the same bit rate with no interference. At 10 Mbps without DWT denoising, FLI results in power penalties of 1.1 to 2.1 dB. These power penalties are completely eliminated by the DWT denoising.

C. DPIM

Like the case of the PPM with the hard decision decoding, the threshold level α is set midway between one and zero levels in the absence of any filtering for the DPIM scheme and is given as [8, 14]:

$$\alpha = RP_{avg}\sqrt{L_{avg}T_b \log_2 L}\,\left(\frac{1}{2}-\frac{1}{L_{avg}}\right); \qquad (10)$$

where L_{avg} is the average symbol length of DPIM.

The number of decomposition level γ can be calculated using (6). The NOPR to achieve a SER of 10^{-6} with the DWT denoising for 4, 8 and 16-DPIM at data rates of 1 - 200 Mbps is given in Fig. 7. Comparing the performance

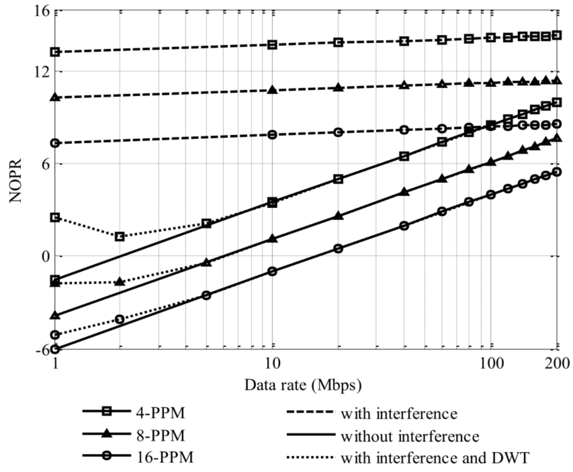


Figure 5: The NOPR versus the data rates for 4, 8 and 16 PPM with the hard decoding scheme with and without the DWT denoising in the presence of the FLI.

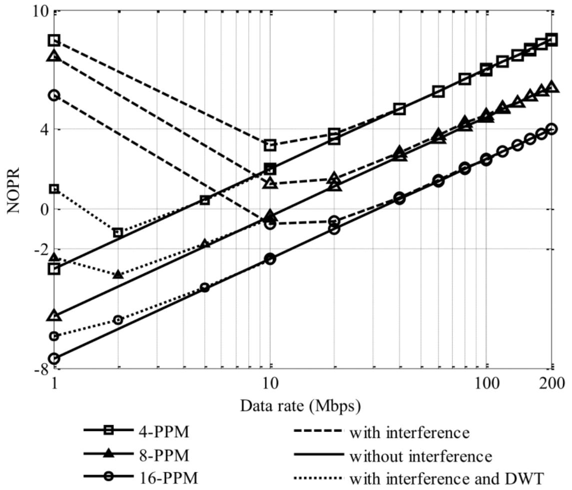


Figure 6: The NOPR versus the data rates for 4, 8 and 16 PPM with the soft decoding scheme with and without the DWT denoising in the presence of the FLI.

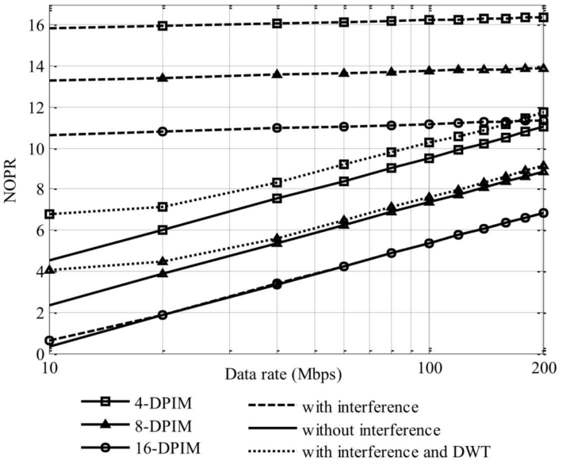


Figure 4: NOPR versus the data rates for 4, 8 and 16 DPIM schemes with and without the DWT denoising in the presence of the FLI.

of the OOK scheme in Fig. 4 and the PPM with the hard decision scheme in Fig. 5, it can be observed that performance of the DPIM scheme with the DWT denoising is intermediate between the OOK and the PPM schemes. Low order of the DPIM shows the performance similar to the OOK with a constant OPP compared to the ideal case. However, higher order of the DPIM shows almost zero OPP like the PPM. The phenomenon is due to progressive reduction of the DC and low frequency components with increasing bit resolutions. Compared to the performance without FLI, the power penalties with DWT are ~ 0.7 dB at a data rate > 40 Mbps for 4-DPIM, which reduces to ~ 0.4 dB for 8-DPIM. The OPPs are reduced to zero by the DWT denoising for 16-DPIM at data rate > 20 Mbps.

V. CONCLUSION

The study of wavelet transform based denoising to reduce the effect of the ALIs for OOK, PPM and DPIM modulation schemes were presented in the paper. The study showed that DWT is very effective in reducing the effect of FLI. The DWT offered a reduction of ~ 5.5 dB in NOPR at 10 Mbps and higher reduction of ~ 7.4 dB was observed at 40 Mbps for OOK. The OPP for OOK is less than ~ 1.6 dB for the data rate > 40 Mbps. The DWT eliminates the fluorescent light induced power penalties for PPM with the hard decision decoding above data rate of 10 Mbps for all bit resolutions. Unlike the case of OOK, the DWT even offer reduction in power penalties at a data rate of 1 Mbps for PPM system. Since PPM with the soft decision decoding scheme showed significant resistance to FLI, the DWT offered reduction in NOPR at data rates < 20 Mbps and no improvement beyond 20 Mbps. The performance of DPIM with the DWT denoising showed the characteristic intermediate between the OOK and the PPM hard decision scheme. Lower order of the DPIM showed performance akin to the OOK with almost a constant OPP above 40 Mbps. However, higher order of the DPIM showed a null OPP above the data rate of 20 Mbps like the PPM.

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