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Channel Estimation for Indoor Diffuse Optical OFDM Wireless Communications

S. K. Hashemi[1], Z. Ghassemlooy[1], L. Chao[2], and D. Benhaddou[3]
[1]Optical Communications Research Group, NCRLab, Northumbria University, Newcastle upon Tyne, UK
[2]Department of Electronic and Information Engineering, Hong Kong Polytechnic University
[3]Engineering Technology Department, College of Technology, University of Houston, USA

E-mail:
seyyedkamal.hashemi@unn.ac.uk, *fary.ghassemlooy@unn.ac.uk*, *enluchao@polyu.edu.hk*, *dbenhaddou@uh.edu*

***Abstract*— Pilot insertion for channel estimation in orthogonal frequency division multiplexing (OFDM) is a promising technique for broadband/high data rate wireless communications. In indoor diffuse optical wireless links, channel impulse response depends on the location of the receiver. For links to offer mobility tracking is essential which can be complex to implement. In this paper we propose channel estimation to allow receiver mobility. We have examined channel estimation with different interpolation methods for OFDM system and have compared the symbol error rates (SER) performance.**

***Index Terms*—Channel estimation, orthogonal frequency division multiplexing (OFDM), Indoor optical wireless communication.**

I. INTRODUCTION

Optical wireless communications (OWC) capable of delivering high data rates for broadband communications has been studied for outdoor and indoor applications including the last-mile broadband access, inter-satellite links and deep-space connections, terrestrial free space optical (FSO) systems, hospital and museums etc. In indoor applications OWC offers a perfect broadband highly secure cellular system where a single wavelength can be used to cover a large are within the same room, adjacent rooms and building, taking advantage of optical signal being confined to a well define area and not passing through opaque obstacle [1]. For indoor applications both infrared (IR) or visible high brightness LEDs can be used, with the latter also offering room lighting as well as a communication link. In Indoor diffuse optical wireless systems with a limited or no line-of-sight (LOS) path the strength of the received signal highly depends on the location of the receiver and objects within the room. Thus, the channel impulse response will vary accordingly. In addition, intersymbol-interference (ISI) due to multipath limits the data rates compared to LOS links. For OWC system using intensity modulation with direct detection (IM/DD), a number of modulation schemes including on-off keying (OOK), pulse position modulation (PPM) and digital pulse interval modulation (DPIM) have been proposed and extensively studied to address some of the above problems [1].

Recently we have seen a growing research interest in application of OFDM for OWC systems [2], [3]. OFDM is a modulation technique, which has been widely used in high data rates RF wireless communications such as wireless LAN (IEEE 802.11a 5-GHz band and IEEE 802.11g 2.4-GHz band), European digital video broadcasting (DVB-T), WiMAX, physical layer in IEEE 802.15.3 wireless personal area network (WPAN) and recently in FSO communication and optical fibre links because of its resilience in a dispersive or multipath channel [2]-[14]. In [4], a low-density parity-check coded OFDM scheme has been proposed for FSO links offering a lower symbol rate and higher tolerance to the deep fades. In [5] asymmetrical clipped optical OFDM has been proposed offering power efficiency compared to the OOK and PPM schemes.

In an OFDM system, a high data rate serial data stream is split into a number of low-rate sub-streams, which are transmitted simultaneously over a number of subcarriers. This parallel transmission gives the ability to alleviate many problems including multipath induced ISI and the need for the complex equalizers. Also orthogonality of subcarrier signals allows frequency overlapping for neighboring subchannels, thus offering highly spectral efficiency. In OFDM channel estimation (tracking) is based on sending pilot signals on predetermined subcarriers in every symbol or transmitting training signals periodically in one symbol [6],[7]. With pilot subcarriers the channel is directly estimated, whereas for subcarriers with no pilot signals channel estimation is performed by means of interpolation using the channel information from neighboring pilot subcarriers.

Recent developments in digital signal processing and VLSI technologies capable of evaluating inverse fast Fourier transform (IFFT) and FFT and executing more than billion floating point operations per second, has made possible practicable implementation of OFDM.

In this paper, we propose an OFDM scheme to combat the ISI and investigate a number of channel estimation techniques to achieve channel tracking. The paper is organised as follows. In the following section OFDM system model is described, followed by different channel estimations schemes presented in section III. The interpolation techniques are outlined in section IV and are compared with the simulation results. An overview of pilot design together with indoor optical wireless channel and its characteristics are discussed in section V. Finally, concluding remarks are given in section VI.

II. OFDM SYSTEM MODEL

In an OFDM transmitter, see Figure 1, serial data streams are grouped and mapped into N_d constellation

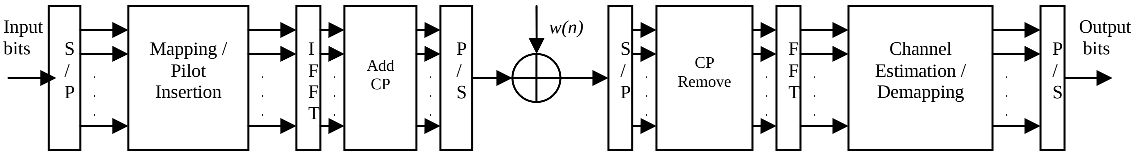

Figure 1. Block diagram of an optical OFDM.

symbols $\{X[k]\}_{k=0}^{N_d-1}$ using BPSK, QPSK or M-QAM. N_p pilots are inserted into the data symbols before being transformed into time domain signal by N orthogonal subcarriers by means of an IFFT given as:

$$x[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X[k] e^{\frac{j2\pi nk}{N}}, \; n = 0, \ldots, N-1. \tag{1}$$

A cyclic prefix of length G (grater than the channel length) is added to the IFFT output to prevent multipath induced ISI.

At the receiver, after removing the cyclic prefix $y[n]$ is applied to the FFT. Due to the cyclic prefix, the linear convolution between the transmitted signal and the channel becomes circular convolution, hence the output of the FFT can be written as multiplication in matrix form given by:

$$\mathbf{Y} = diag(\mathbf{X}).\mathbf{H} + \mathbf{W}, \tag{2}$$

where $\mathbf{H} = \mathbf{F}.\mathbf{h}$ is the frequency response of the channel with the length L, $[\mathrm{F}]_{n,k} = N^{-\frac{1}{2}} e^{-\frac{j2\pi kn}{N}}$ is the FFT matrix and $\mathbf{W}_{\mathbf{Nx1}}$ is the white Gaussian noise with $E[\mathrm{WW}^H] = \sigma_n^2 \mathrm{I}_N$ [8]' H is the Hermitian transpose and *diag* is the diagonal matrix.

III. CHANNEL ESTIMATION

In the block type channel estimation, a known training sequence $\mathrm{X_{TS}}$ is sent periodically and all subcarriers are used as the pilots. The least-square (LS) and the minimum mean square error (MMSE) are used to estimate the channel from the received training sequence by minimizing the error $\min \|\mathrm{Y} - \mathrm{XH}\|^2$ [9]:

$$\hat{\mathrm{H}}_{\mathrm{LS}} = \mathrm{X}_{TS}^{-1} \mathrm{Y}_{TS}, \tag{3}$$

$$\hat{\mathrm{H}}_{\mathrm{MMSE}} = \mathrm{F}\left(\mathrm{R}_{hh} \mathrm{F}^{\mathrm{H}} \mathrm{X}_{\mathrm{TS}}^{\mathrm{H}}\right)\left(\mathrm{X}_{\mathrm{TS}} \mathrm{F} \mathrm{R}_{hh} \mathrm{F}^{H} \mathrm{X}_{\mathrm{TS}}^{\mathrm{H}} + \sigma_n^2 I_N\right)^{-1} \mathrm{Y}_{TS} \tag{4}$$

where $\mathrm{R}_{hh} = E[hh^H]$ is the auto-covariance matrix of the channel. With no prior knowledge of $\mathbf{R}_{hh}$, using the low-ranking approximation of the covariance matrix given by singular value decomposition the estimator can be simplified without the need for matrix inversion [10].

In the comb-type channel estimation, N_p pilots X_P are inserted in the subcarriers. The LS and the maximum likelihood (ML) channel estimations can be obtained by [11], [6]:

$$\hat{\mathrm{h}}_{\mathrm{LS}} = \left(\mathrm{F}_P^H \mathrm{F}_P\right)^{-1} \mathrm{F}_P^T \mathrm{X}_p^{-1} \mathrm{Y}_P, \tag{5}$$

$$\hat{\mathrm{h}}_{\mathrm{ML}} = \left(\mathrm{F}_P^H \mathrm{Q}_{Xp} \mathrm{F}_P\right)^{-1} \mathrm{F}_P^T \mathrm{Q}_{Xp} \mathrm{X}_p^{-1} \mathrm{Y}_P, \tag{6}$$

where $\mathrm{Q}_{Xp} = diag(|X_p(0)|^2, \ldots, |X_p(N_p - 1)|^2)$, $\mathbf{F_P}$ is $N_P \times L$ which denotes the FFT matrix with entries of $[\mathrm{F_P}]_{n,l} = N^{-\frac{1}{2}} e^{-\frac{j2\pi nl}{N}}$ and T denotes the transpose.

IV. CHANNEL INTERPOLATION

In rapidly changing channels the comb-type pilot insertion scattering pilots in time and frequency domain usually performs better than the block pilots to track the time variation of the channel. Once the channel gain at the pilot symbol positions is obtained from the received signal, interpolation is applied to derive the channel state information at data symbol positions. The channel should be sampled according to the Nyquist theorem; therefore the spacing of the pilots in time and frequency should satisfy the following requirements:

$$d_f \le \frac{1}{2\Delta f \tau_{\max}}, \tag{7}$$

$$d_t \le \frac{1}{4 f_{D,\max} T_{symbol}}, \tag{8}$$

where d_f and d_t are the pilot spacing in frequency and time, respectively, $\tau_{\max}$ is the maximum excess delay, Δf is the subcarrier spacing, T_{symbol} is the total symbol duration and $f_{D,max}$ is the maximum Doppler frequency [12].

Interpolation can be done both in time and frequency domains. In time domain, FFT interpolation is used to estimate the channel and suppress the noise. Initially, frequency domain channel estimate is converted to the time domain using IFFT. Using signal processing technique and the orthogonal basis the received pilot symbols are adjusted and the higher delay components longer than the known delay tap are suppressed. Full channel estimation is performed with the FFT transform back to the frequency domain. Other techniques operating in the frequency domain using the linear interpolation, low-pass interpolation, second-order polynomial, and the spline cubic interpolation have been investigated in [9]. In two-dimensional (2D) estimation scheme, pilots are inserted both in time and frequency domains that give improved performance than one dimensional (1D) at the cost receiver complexity. In [13] both 2D Wiener filter interpolation and LS have been proposed. Figure 2 compares the simulation results for the SER performance for different interpolation schemes (nearest, linear, cubic spline and time domain) for an OFDM system with QPSK using the LS estimation with 256 subcarriers, 32 pilots and 128 data symbols over a random channel with 16 taps. The best performance is offered by the time domain interpolation as in [9].

V. PILOTS DESIGNE

In [7] it has been shown that the optimal sequence for the channel estimation could be any equal magnitude sequence. Pilots can also be inserted uniformly (equispaced) or in clustered form with different pattern. The effect of noise on the pilots increases the estimation error, thus degrading the system performance. This effect can be mitigated by oversampling the channel with more pilots. This technique will reduce the total data throughput because more subcarriers are employed to transmit the pilots. Alternatively, one could increase the power level of the pilot signals. To ensure the same power level, the power level of data signal has to be reduced, leading to reduced E_b/N_o. To find the optimal number of pilots, there is a tradeoff between the channel estimation accuracy and the bandwidth efficiency. The total transmitting power is given by:

$$N\varepsilon = N_p\varepsilon_p + N_d\varepsilon_d \tag{9}$$

where ε, ε_p and ε_d are the average power of all transmitted symbols, pilot and data symbols, respectively. Normalizing to the total average power and considering $N = N_p + N_d$, the power of data and pilots can be obtain from (9) in terms of the pilot-to-data power ratio given by:

$$\varepsilon_d = \left(1 + \frac{N_p}{N}\left(\frac{\varepsilon_p}{\varepsilon_d} - 1\right)\right)^{-1}, \tag{10}$$

$$\varepsilon_p = \frac{\varepsilon_p}{\varepsilon_d}\left(1 + \frac{N_p}{N}\left(\frac{\varepsilon_p}{\varepsilon_d} - 1\right)\right)^{-1}, \tag{11}$$

Equations 10 and 11 can be used for power allocation to minimize the appropriate BER with respect to $\varepsilon_p / \varepsilon_d$ for a given SNR [7], [14]. In adaptive pilot schemes, estimate of the maximum delay spread is required in order to change the number of pilots and their spacing. This is not necessary for the wireless optical channel because of slow time varying channel characteristics.

VI. OPTICAL OFDM

Since OFDM signal format is bipolar, therefore it can not be used in OWC systems that uses IM. To ensure that an OFDM signal is unipolar a sufficiently large DC bias is added to it. In [3]-[5] more efficient and practical systems based on the asymmetrically clipped, clipped and unclipped OFDM signals have been proposed for IM applications that are more resilient in a dispersive channel.

VII. OPTICAL CHANNEL SIMULATION

The system performance of a communication system can be improved by means of enhanced channel characterization. The propagation characteristics of optical channel differ from the conventional radio frequency channel and the photodetector integrates the optical intensity field over an area of millions of square wavelengths. In diffuse indoor OWC links the transmitted optical signal (pulse) will undergo scattering, reflection and diffraction arriving at the detector with attenuation and dispersion. The percentage of the reflections depends on the material reflection coefficient ρ $(0 \le \rho \le 1)$. The reflection pattern is considered as Lambertian or Phong's model [15],[16]. The latter describes surfaces with strong specular components. The channel impulse response is separated into LOS and diffuse (multiple reflections) elements.

Received optical power from the primary reflection is expressed as:

$$P = P_t \sum_{i,j} \frac{(m+1)^2}{4\pi^2 r_i^2 r_j^2} .\rho_i A_i A_r .\cos^m(\phi_i)\cos^m(\phi_j)\ \cos(\theta_i)\cos(\theta_j)\,\delta(t - \Delta t_{ij}) \tag{12}$$

for $\phi_i / \phi_j \in [-\pi/2, \pi/2]$ and $\theta_j \in [0, FOV^\circ]$,

where P_t is the optical transmitted power, ϕ is the angle of irradiance with respect to the transmitter axis, θ is the angle of incidence with respect to the receiver/surface axis, r_i / r_j is the distance between the optical source and receiver/surface, A_i is the surface elements area, ρ_i is the i^{th} surface element reflective index and m is the Lambert order.

In our simulation a room with a size of $5 \times 5 \times 3$ m^3 is considered and its surfaces are divided into N_s elements. The transmitter located in the middle of the ceiling at the height of 2.5 m from the floor and transmitting 1 W of power. The receiver is located at (0.5, 1, 0) m with a surface area A_r of 1 cm^2 and responsivity R of 1 A/W. The reflection coefficients of the side walls are 0.8. Both transmitter and receiver are oriented vertically, and the radiation patter is assumed to be Lambertian of order $m = 1$. The sampling time Δt is set at 0.2 ns to separate the two neighboring elements by 6 cm. Each cell of the side walls is considered as receiver at first, then as an alternative transmitter that attenuates the reflected power. Figure 3 depicts the frequency response for the primary reflection for a range of receiver field-of-view (FOV). Wider FOV offers higher channel gain but at the cost of reduced channel bandwidth (from 155 MHz at FOV of 10^o to 9 MHz at FOV of 90^o). Figure 4 illustrates the received reflected power against the FOV increases with the FOV before reaching a saturation level of $0.50409\,\mu W$ at FOV of 90^o.

VIII. CONCLUSION

Channel estimation for optical wireless OFDM system was presented. Temporal dispersion caused by multipath and the dependence of the channel impulse response to the location of the receiver affects the performance of the system, particularly at high data rates. In addition, changing FOV of the receiver also affects the frequency response. A number of channel estimation techniques for OFDM OWC links were outlined and the proposed system was simulated. The SER performance for different schemes was compared to the interpolation scheme based on the time domain offering the best performance.

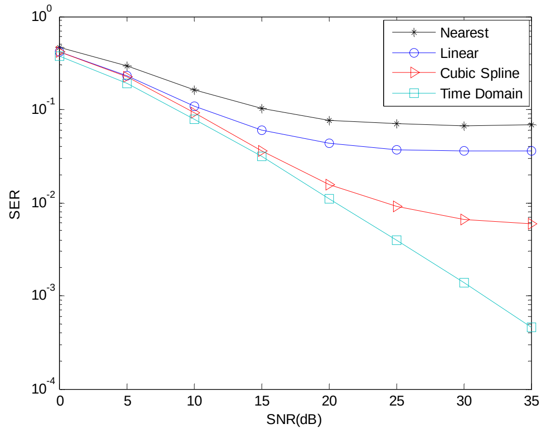

Figure 2. SER for OFDM system against the SNR for different interpolation schemes.

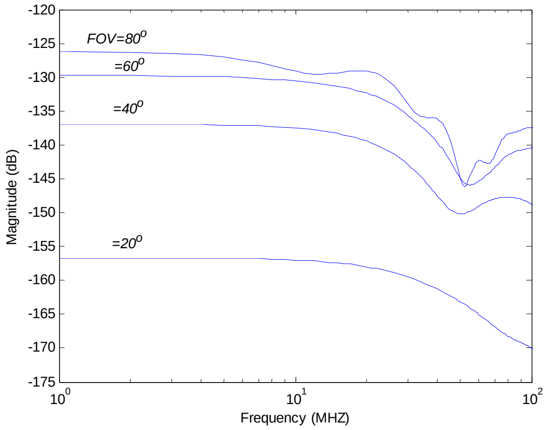

Figure 3. Optical channel impulse response for a range of *FOVs.*

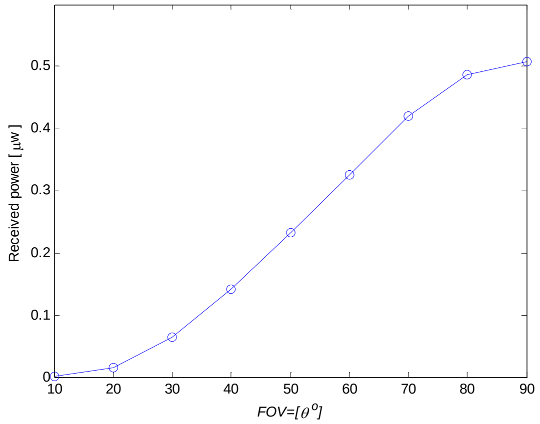

Figure 4. Received power from the primary reflection against the *FOV*.

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