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Energy efficiency of visible light communication using SEE-OFDM

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Abstract: *Wireless internet access technology can experience a major revolution through the use of breakthrough technology of Visible Light Communication (VLC) or Li-Fi (light fidelity) which could promise much higher data rates and better security and integrity of the data at the physical layer. There are many challenges being faced when visible light communication is being used resulting in low efficiency of the system. The main purpose of this paper is to endeavour to achieve highest data rate possible in an indoor environment while tackling problems which include loss of energy efficiency as OFDM is made unipolar and real-valued.A novel unipolar scheme called 'Spectral and Energy efficient' (SEE-OFDM) is proposed which is compatible with IM/DD wireless systems and is a great candidate for VLC. SEE-OFDM delivered promising results as it doubles the spectral efficiency of unipolar OFDM format. The fundamental idea is to generate multiple signals and sum them; both even and odd subcarriers are transmitted to carry information and the signal remains immune to interference. It is an attractive choice since higher data rates and SNR are gained, with a significant reduction in PAPR relative to conventional ACO-OFDM.*

Keywords: *Li-fi, Visible Light Communication, energy-efficiency, OFDM, LED, Clipping.*

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1. Introduction

Limited channel capacity and low transmission rate of traditional radio systems is the result of limited availability of radio spectrum. With the usage increasing exponentially, higher data rates are being demanded by users. The optical band of is available which is untapped and can provide promising solutions in the near future by being able to provide tens of gigabit per second [1] specifically suitable for indoor settings. Uplink traffic and downlink traffic is expected to more symmetrical.

Visible Light Communications can solve the bandwidth limitation problem [2] and have many advantages relative to radio systems such as:

•Abundant capacity as VLC system has an inherent nature of being immune to interferences.

•Frequency reuse is a possibility.

•VLC system is a secure system and promises integrity of data as light cannot penetrate through opaque objects.

•Hardware design is already integrated as luminaries so low cost system.

•License free bandwidth of hundreds of terahertz.

• Has no ill effects on humans or other electronic devices.

Modulation of optical carrier in VLC is done through employment of IM/DD techniques where the instantaneous power of the LED/LD is modulated by the baseband signal (real-valued) and the photodetector directly detects it. This means that the transmission of data essentially takes place in the intensity domain with absence of information in phase or frequency domain. A lot of single-carrier modulation techniques such as on-off keying (OOK) and pulse-position modulation were explored in literature to achieve hundreds of Mbps but multipath propagation causes inter-symbol interference in these techniques which is a serious disadvantage. The operation is also bandwidth-limited as the modulation bandwidth of off-the-shelf LED is restricted which hinders the upgradation of data rate of single-carrier techniques to 1 Gbps.

Hence, it is concluded that a multi-carrier and spectrally efficient modulation scheme is required to achieve robust Gbps networks and orthogonal frequency division multiplexing (OFDM) is the most attractive candidate in this regard. It supports high data rates through orthogonal subcarriers that carry multi-level quadrature amplitude modulation symbols (M-QAM). OFDM signals have an inherent high peak-to-average power ratio (PAPR) which lead to non-linear distortions due to restricted dynamic range of illuminating optical sources hence several efforts are directed in this area by researchers. Another challenge is to ensure that the baseband OFDM signal is unipolar (positive) and real valued so that DC-biasing technique has to be omitted as it leads to compromises on energy efficiency of the technique. Therefore, modification of RF-OFDM is required for compatibility with IM/DD system [4][5].

Imposition of Hermitian symmetry in the frequency domain is the most straightforward and common method employed on subcarriers of IFFT block. However, DC-bias is required as the signal generated is still bipolar. Asymmetrically clipped OFDM (ACO-OFDM) [11] and Flip-OFDM [12] are among the solutions that devise to unipolar OFDM formats and eliminate the need for cancellation at the receiver or interference estimation but a loss of half the spectral efficiency is the compromise. This causes the data rate to be reduced to half as the two factors i.e. data rate and spectral efficiency are directly proportional.

A novel OFDM format is proposed in [6] where both the even and odd subcarriers of IFFT operation are functional in carrying data. Multiple signals are generated through use of odd-indexed subcarriers by employing different IFFT lengths (inspiration derived from ACO-OFDM) and the transmitter and receiver carry out construction and reconstruction steps respectively. N is the maximum IFFT length. Different paths are used and the addition of signals takes place before their transmission. Summation at a fixed mean power-per-time domain leads to a significant reduction in PAPR through distribution of power among the signals. DC-bias operation is maintained by clipping of negative values by the transmitter through signal conditioning as data is carried on both odd and even indexed subcarriers formerly [7]. Fast Fourier Transform (FFT) is required by the receiver once and the length is N. Clipping interference is eliminated through reconstruction at the receiver. Hence, it can be concluded that the use of SEE-OFDM is the perfect choice as it promises higher data rates, reduces PAPR significantly, has no DC-bias and the computational complexity is minimally increased.

In section (2) we discuss the SEE-OFDM transmitter in detail and the step by step procedure of generating two paths and mark a clear distinction in the ways they are transmitted to ensure unipolarity of the signals. Section (3) discusses how the receiver has to be deployed in order to receive signal with optimum synchronization through removal of cyclic prefix. The evaluation for effectiveness of the SEE-OFDM system relative to ACO-OFDM is illustrated in section (4) and CDF plots of PAPR evidence the energy efficiency. BER v SNR plots are illustrated for the proof of increase in SNR below the FEC limit (10^-3). We end with conclusions and future work in section (5).

2. SEE-OFDM Transmitter

The transmitter of a conventional OFDM is redesigned to add explicit functionalities to it and the modifications are described in this chapter. Two different paths are used for generation of two unipolar real-valued signals as we assume two-path approach for summation of signals for generation of SEE-OFDM signal. Figure 1 illustrates the building blocks of the SEE-OFDM transmitter [6].

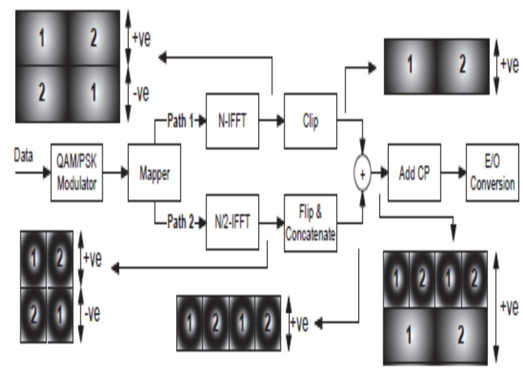


Figure 1: SEE-OFDM (two-path approach)

ACO-OFDM [3] building blocks are incorporated into the first path and methodology of generation of signal is almost similar to it. Since Quadrature-Amplitude-Modulation (QAM) or Phase Shift Keying (PSK) constellations are used, bit symbols grouped into zeros and ones form the input data stream. The mapper block maps the generated QAM/PSK symbols into the vector:

$$X_k = [\,0\; X_0 \ldots\ldots 0\; X_{N/4-1}\; 0\; X^*_{N/4-1}\; 0 \ldots\ldots X^*_0\,]^T \quad (1)$$

where the complex conjugate is denoted by (.)*, vector transpose is denoted by (.)T and the frequency domain input symbols are represented by X_k, $k = 0, \cdots, N-1$ values. To insure real-valued signal, Hermitian symmetry property of vector X is employed to the process of mapping the QAM/PSK symbols to only odd-indexed subcarriers of length N of IFFT operation. Hermitian property is ensured when the values of first and N/2 subcarriers are also zero. Inverse Fast Fourier Transform (IFFT) of the vector X_k, is taken to generate the time-domain signal at the output:

$$x_n = \frac{1}{N}\sum_{k=1}^{N} X_k \; exp^{\left(j\frac{2\pi}{N}nk\right)} \quad (2)$$

where the time-domain samples at the output are denoted by x_n, $n = 0, \cdots, N-1$. Half-wave symmetry is seen in the generated time-domain signal as only odd subcarriers contained the data by vector *Xk*.. Half wave symmetry offers the advantage that clipping causes no loss of information as information is retained in the second half of the sample as it is in the first N/2 samples. Unipolar signal is produced by clipping [8]. Intermodulation is a serious complication caused by clipping in which sum and difference frequencies which do not exist in the original signal are generated as different signals mix. This challenge is mitigated in this technique as intermodulation affects the even indexed subcarriers only and the odd-indexed (data-carrying) subcarriers remain immune to it.

Same technique is repeated in second path and the IFFT operation uses a length of N/2 as illustrated in Figure 1. However, the procedure of signal clipping to produce unipolar signal is replaced by another procedure where time-domain, N length OFDM symbol is generated by flipping the polarity of the negative samples followed by horizontal concatenation with the positive samples. Construction/ conditioning steps are followed by summation of signals. Inter-carrier interference (ICI) and inter-block interference (IBI) are avoided through addition of a cyclic prefix (CP) as it ensures circular convolution instead of linear convolution with the channel [9]. Modulation of the intensity of LED takes place after the digital-to-analogue converter (D/A) converts the unipolar signal into an analogue signal [10]. Higher data rate is achieved as the two paths are added and the data rate achieved is calculated by:

$$R_{total} = R_{path\,1} + R_{path\,2}$$

$$= \left(\frac{N/4 + N/8}{N + N_{CP}}\right) B \log_2 M \qquad (3)$$

Where B is denoted by bandwidth; number of time-domain samples for cyclic prefix is denoted by N_{CP} and modulation order of QAM/PSK is denoted by M.

3. SEE-OFDM Receiver

Figure 2 illustrates the building blocks of the SEE-OFDM receiver. Reconstruction steps is the first step followed by application of N FFT operation on a single length. Intermodulation resulted by clipping which occurs in the first path also occurs in the second path on the even-indexed subcarriers thus reconstruction steps are used to eliminate intermodulation [6].

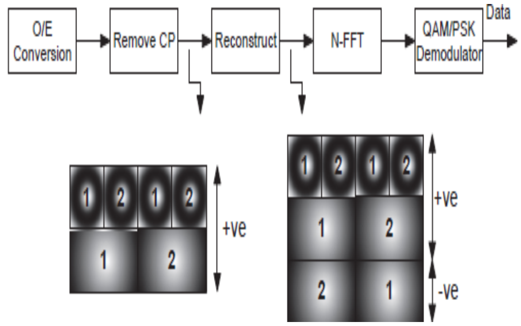


Figure 2: SEE-OFDM Receiver (Two-paths approach)

Representation of time-domain signals at the receiver after photodiode (PD) (an optical detector) employs optical-to-electrical conversion is expressed as:

$$y[n] = x[n] \otimes h[n] + z[n] \qquad (4)$$

Signal-to-noise ratio per sample received in two-paths SEE-OFDM is obtained by:

$$SNR = \frac{\sigma_x^2}{2\,\sigma_z^2} = 20\,\log_{10}\frac{\sigma_x}{2\sigma_z} \qquad (5)$$

where the transmitted signal power is denoted by σ_x^2.

The data rate can be increased using an additional path i.e. three-paths SEE-OFDM using the same procedure mentioned above. The achieved data rate and SNR per sample received is given by (6) and (7) respectively.

$$R_{total} = R_{path\,1} + R_{path\,2} + R_{path\,3}$$

$$= \left(\frac{N/4 + N/8 + N/16}{N + N_{CP}}\right) B \log_2 M \qquad (6)$$

$$SNR = \frac{\sigma_x^2}{3\,\sigma_z^2} = 20\,\log_{10}\frac{\sigma_x}{3\sigma_z} \qquad (7)$$

A theoretical approach for estimation of noise penalty with respect to signal variance is stated in [7] as it provides a widely known bit-error rate (BER) formula for M-QAM symbols. Plugging (6) and (7) into this formula reveals that 6 dB of noise penalty is obtained for two-path SEE-OFDM and 10 dB for three-path SEE-OFDM approach with the signal variance twice and thrice as much respectively when compared to single-path OFDM.
The effective SNR is reduced due to clipping noise power and SNR_{eff} is given by:

$$SNR_{eff} = \frac{\sigma_x^2}{\sigma_z^2 + \sigma_c^2} \qquad (8)$$

4. Simulation Results

The validation for achievement of higher data rate, low peak-to-average power ratio (PAPR), lower bit-error rate (BER) and high spectral efficiency for two-path and three-path SEE-OFD is carried out in the simulation stages to confirm the theoretical data obtained to choose the better candidate among the two approaches for achievement of high energy-efficiency of visible light communications systems through employment of Monte Carlo simulations on 16 carriers using uncoded QAM constellations with modelling of thermal and shot noise done through addition of noise power at AWGN to obtain realistic results and then the parameters mentioned would be compared to the ACO-OFDM technique proving that SEE-OFDM is the better and a relatively spectrally efficient choice.

The advantage of using Monte Carlo simulations is that the results obtained are very accurate. In this numerical method, the propagation path of light is modelled probabilistically as photon packets or virtual photons represent light. Large generation of such photons enable greater accuracy and reliability of results.

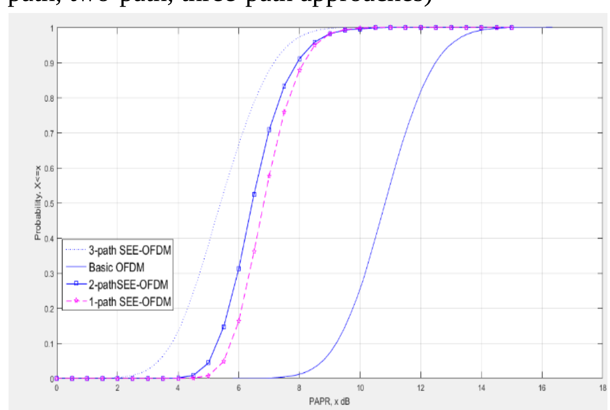
PAPR is a distinctive non-desirable feature of OFDM and reduces the efficiency of the system. The clipping technique is one of the approaches to reduce PAPR which is used in the first path of this technique. However, it can cause out-of-band and in-band interferences hence reconstruction technique has to be employed at the receiver. The following parameters were kept constant for fair comparison:

-Monte Carlo simulations are used and the number of subcarriers is fixed to 16 to fairly compare the single, two and three path approaches to obtain higher simulation speed and more reliable results
-The QAM constellations are fixed to obtain a fixed data rate.
-The value of average power obtained over the OFDM symbol is kept equal and then average power is distributed effectively over the paths.
-To ensure complete practicality of the simulations, AWGN with a value of 15dBm is maintained at receiver which compensates for shot and thermal noise.
-A line-of-sight (LOS) configuration is assumed.
-The length of QAM symbol (without cyclic prefix) is kept longer than the h(t) of the channel i.e. the channel impulse response to avoid ISI.
-The CP length is chosen to ensure that its duration is equal to or longer than the h(t) spread.

Simulations are conducted to comprehend the effect of summation of additional paths on PAPR that modulates the LED signal. CDF stands for cumulative distribution function and is a various parameter probability distribution function and is used in standard practice to investigate the PAPR value. Figure 3 demonstrates the CDF plot for the three approaches of one-path, two-path and three-path approaches of SEE-OFDM. It is noticed that the two-path approach has a lower PAPR value than single path when the number of subcarriers is fixed. A reduction of 1.5 dB can be owed to the split of average power between the two paths as summation takes place at a fixed value of average power of OFDM. The three-path approach demonstrates the lowest PAPR (value of 2.3 dB) relative to single path and two-path approach as illustrated by the dotted line plot in Figure 17. The goal is to achieve the lowest PAPR as dynamic range of LEDs is quite limited. It should be noted that one-path SEE-OFDM is essentially similar to ACO-OFDM so is used as a benchmark in all the simulation results for fair comparison.

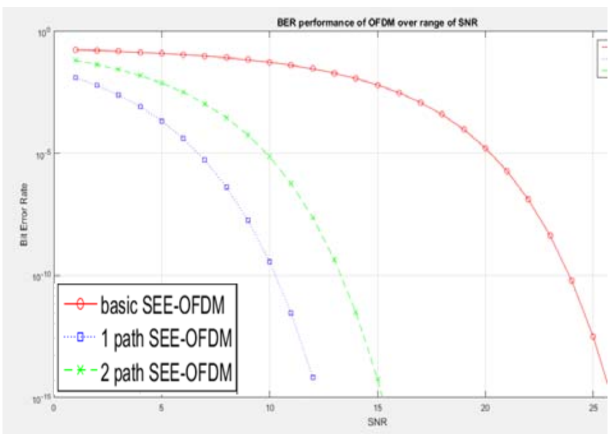
The core ideas of how our infrastructure supports automated context-driven composition of pervasive services are discussed in this section. The concepts of taking into account the capabilities and limitations of a device, resource awareness and user preferences in a specific context are illustrated by means of an example. We also provide an outline of our algorithm to discuss the steps taken to deploy a customized pervasive service and mention implementation details.

Figure 3: CDF plot of PAPR for SEE-OFDM (one-path, two-path, three-path approaches)



Now BER is discussed which stands for bit-error rate and performance is measured by the BER plotted as a function of SNR. Figure 4, Figure 5, Figure 6 and Figure 7 are the plots of BER vs SNR of various paths of SEE-OFDM and are obtained through Monte Carlo simulations. The standard reported values for Optical Wireless Communications in indoor settings is in agreement with the SNR values plotted in the graphs which range from 10 dB to up to 50 dB in simulation. The difference between the plots is that BER v SNR graphs are plotted for different values of bits per subcarrier. The SNR gain is easily calculated and compared using these graphs. The graphs for one-path SEE-OFDM and two-path SEE-OFDM. A common trend is observed that at a given data rate, the two-path SEE-OFDM evidences a superior BER performance when QAM constellations are of higher order. The target BER for determining the performance is the BER value of 10^-3 (should be below the Forward Error Correction (FER) limit). The plot for single path using 6 bits and two-paths using 4 bits in Figure 4 indicates a SNR gain of about 3.5 dB. In Figure 5, the BER vs SNR is plotted for single-path, 3-bits and two-path 2-bit per subcarriers and the SNR gain is measured. It is indicated that there's a SNR gain of almost 4 dBs in this system. Figure 6 is the BER vs SNR plot of two-path 6 bits, one-path 9 bits per subcarrier and achieves a 5dB SNR gain. Figure 7 uses 8-bits and 12 bits per subcarrier for single and two paths respectively and achieves a gain of 9 dB. It also indicates an immense improvement from the conventional OFDM SNR proving the effectiveness of the two-path SEE-OFDM.

Figure 4: BER vs SNR for two-paths 4 bits, one -path



6-bits per subcarrier.

Figure 5: BER vs SNR plot for two-path 2 bit, one-path 3 bit per subcarrier.

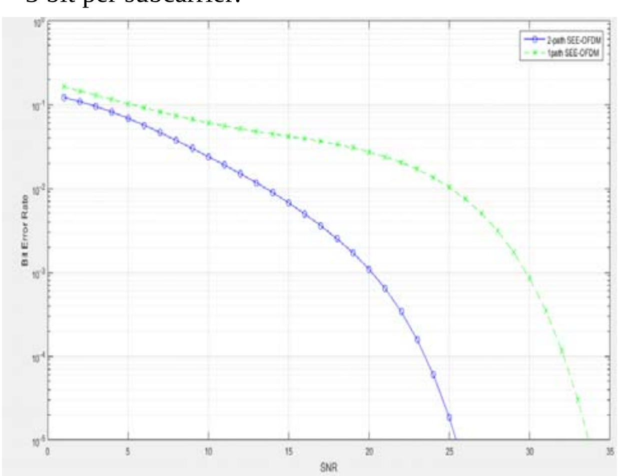
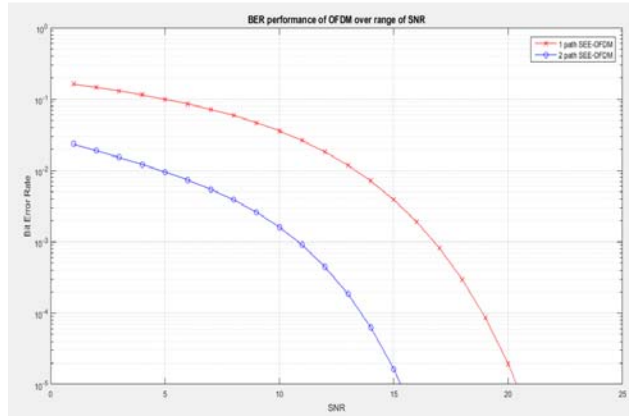


Figure 6: BER v SNR plot of two-path 6 bits, one path 9 bits per subcarrier



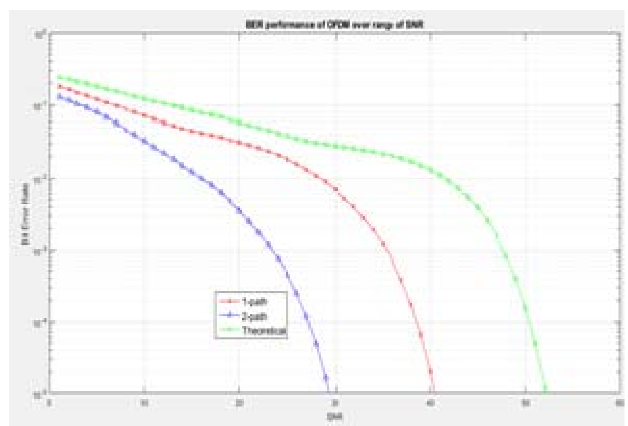


Figure 7: BER vs SNR plot of two-path 8 bits, one-path 12 bits per subcarrier. (Theoretical simple OFDM value also plotted, square block).

The effectiveness of the addition of third path is tested in Figure 8. The effective data rate is kept the same and the three paths are plotted using 9 bits for one-path approach, 6 bits for two-path approach and 5 bits for three-path approach. The BERs of the three approaches is measured at 10^-3 BER. The three-path approach is found to be better than one-path approach by 3 dB gain in SNR as its BER is better. However, the two-path approach dominates again with about 2.5 dB gain in SNR relative to three-path approach. This occurs due to the slight increase recorded in signal power at the receiver as a 10 dB SNR penalty is imposed on three-path approach following the reconstruction steps that take place at the receiver. The results thus prove that the two-paths SEE-OFDM is the most attractive choice as the SNR gain in dB is the highest when simulations were carried out using this approach.

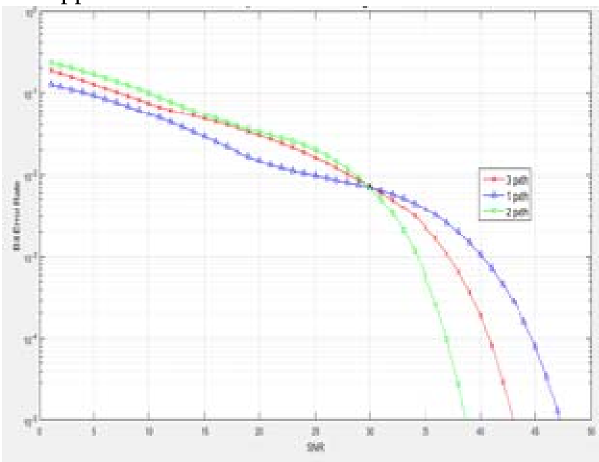


Figure 8: BER vs SNR for the three approaches

5. Conclusion and future work

The design methodology of Spectral and Energy efficient SEE-OFDM is analysed in the optical IM/DD transmission environment. SEE-OFDM is tested in the context of single-path, two-path approach and three-path approach and the plotted results evidenced for the efficiency of each system to verify the claims.

Simulation results are in agreement with desired objectives as DC bias is eliminated and there's a stark increase in spectral efficiency of the system, up to 90%. A high SNR and a low BER is the ideal trade-off and using two-path SEE-OFDM, a 9 dB gain is demonstrated while successful reduction of PAPR by 2.5 dB takes place relative to the widely-known ACO-OFDM. Therefore, it can be concluded that two-path SEE-OFDM is the best candidate among all three approaches as it delivers the best results and reports for the highest efficiency.

The advantage of this system lies in the low complexity of the design and easy synchronisation as the transmitted symbols are easily recovered at the receiver without any cancelation or interference estimation. Throughout the simulation, the results obtained are in agreement with the standard SNR range for indoor optical wireless communications and BER is constantly maintained below FEC limit. Thus, the spectral efficiency of SEE-OFDM is proved making it an attractive choice.

Further work could include addition of more paths to the SEE-OFDM while minimizing the SNR penalty at the receiver. SEE-OFDM can also be integrated with MIMO or dimming systems to enhance its power efficiency.

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