

Optical Wireless Bandwidth Efficiency Enhancement Using Interval Shift Key

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ABSTRACT - Optical wireless communication is an emerging technology that has generated a vast number of interesting solutions to very complicated communication challenges. For example high data rate, high capacity, unlicensed spectrum, high security and minimum interference links. The optical systems are significantly different from radio frequency channels where amplitude, frequency and carrier phase are modulated, in optical signal the intensity is modulated. Unfortunately, optical sources suffer from long rise/fall times such as in light emitting diodes. This leads to inefficient utilization of optical communication bandwidth. Consequently, the modulation bandwidth is restricted to only few megahertz's. Additionally, optical detectors exhibit large capacitance that prohibits high data rate. Moreover, the optical transmission power is limited by factors such as human eye safety and power consumption limits. In this paper, a modulation technique named Interval Shift Key (ISK) is used to modulate subcarriers of optical orthogonal frequency-division multiplexing (OFDM). This technique improves the bandwidth utilization and power efficiencies and reduce bit error rate (BER). The MATLAB software is used in this study to simulate BER and power efficiency in an adaptive white Gaussian noise channel. The technique is validated by comparing simulated and published results where good agreement is achieved.

Keywords: *Optical wireless communication, Optical OFDM, modulation, interval shift key, bandwidth efficiency, power efficiency.*

المستخلص- الاتصالات الضوئية اللاسلكية هي التكنولوجيا الناشئة التي وفرت عددا كبيرا من الحلول لتحديات الاتصالات المعقدة. مثل ارتفاع معدل نقل البيانات، السعات العالية، الطيف الكهرومغناطيسي غير المرخص، تأمين المعلومات بصورة كبيرة والحفاظ على أقل مستوى من تداخل قنوات الاتصالات. إن قناة الإتصال الضوئية اللاسلكية تختلف اختلافا كبيرا من قنوات الإتصال الراديوية حيث يتم تضمين مطال أول تردد أو طور الإشارة الحاملة، بينما يتم تضمين شدة الضوء في الإشارة الضوئية اللاسلكية. لسوء الحظ، تعاني مصادر الضوء من طول زمن صعود و هبوط النبضة كما في الثنائيات الباعثة للضوء وهذا يؤدي الى استخدام غير مثالي للطيف الضوئي اللاسلكي ونتيجة لذلك، فإن عرض نطاق التضمين محدود بعدد قليل من الترددات. بالإضافة إلى ذلك، فإن الموسعة العالية لمستقبلات الضوء تحظر معدل البيانات العالية. أكثر من ذلك فإن الطاقة الضوئية محدودة بعدد من العوامل، منها اجراءات سلامة العين و وحدود استهلاك الطاقة. في هذه الورقة، تم استخدام تقنية للتضمين تسمى *Interval Shift Key (ISK)* تستخدم لتضمين الحوامل الجزئية من الاتصالات البصرية متعامدة التردد (*OFDM*) تحسن هذه التقنية من استغلال عرض النطاق الترددي وكذلك كفاءة استخدام الطاقة، كما تساعد في تخفيض معدل ظهور الأخطاء (*BER*). تم استخدام برنامج *MATLAB* في هذه الدراسة لمحاكاة مدل ظهور الأخطاء ومعدل استهلاك الطاقة في قناة ضجيج جاوس. تم التحقق من صحة هذه التقنية عن طريق مقارنة نتائج المحاكاة حيث تم التوصل لمخرجات جيدة.

INTRODUCTION

Recently, global communication networks have been greatly expanding. In particular broadband networks that led to the deployment of advanced communication system using wireless optical

wavelength. Optical wireless (OW) known as free space optics or sometimes known as free space photonic, represents one of the most promising approaches for addressing the emerging broadband access network both indoor and outdoor^[1]. The

underlying concept of OW is very simple, utilize optical beams to carry data through atmosphere or vacuum. As a result, OW link architectures are very similar to the optical fiber communication point to point links, with the absence of optical fiber cables. Hence optical wireless communication offers advantages of both wireless and optical fiber communication^[2].

The radio frequency applications are limited due to the scarcity in available bandwidth as well as high licensing cost. On the other hand, the optical domain possesses huge unlicensed bandwidth that is in excess of 200 THz. Moreover, due to confinement of optical beam within close walls, the same wavelength or a range of wave lengths could be reused within the same room and neighbouring rooms without inter-channel and adjacent channel interference. Additionally, the optical spectrum is immune to electromagnetic interference (EMI) and hence the optical wireless communication (OWC) is suitable in the environment where sensitive equipment need to be protected from electromagnetic interference^[3].

Optical wireless system basically consists of data source and destination, modulator and demodulator, light sources and photo detector. Figure 1 shows a block diagram of optical wireless system^[4].

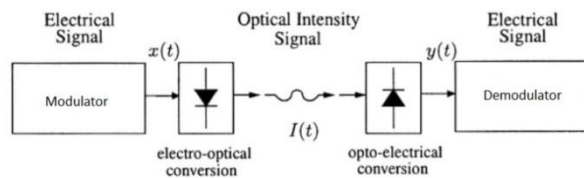


Figure: 1 Block diagram of basic optical wireless communication system

From Figure 1 it is evident that the optical wireless channel is significantly different from radio channel. The conventional modulation techniques adopted in RF channels such as amplitude, phase and carrier frequency modulation cannot be directly applied in optical channels.

In optical systems the information signal or its modulated version may be used to directly modulate the optical carrier signal using intensity. This is known as intensity modulation with direct detection (IM/DD). Electrical modulations in conjunction with the IM/DD are used with Optical wireless systems (indoor or outdoor) due to its simple implementation and low cost^[5].

Unfortunately, light emitting diode (LED) which normally used as transmitters in optical wireless systems has high rise/ fall time. This leads to reduced modulation bandwidth to only few megahertz's and prohibits the use of large number of band limited pulse shapers. Also, the bandwidth of high data rate systems is limited by the capacitance exhibited by large area photodiodes which used as receivers in optical systems^[5]. Moreover, the transmission power used in OWC (mainly indoor) is limited by numerous factors such as eye safety, physical devices limitations and power consumption^[5].

Both quadrature amplitude modulation (QAM) on discrete multi-tone (DMT) and multi-level pulse amplitude modulation (PAM) are spectrally efficient modulation schemes suitable for LED based communication but they are less power efficient. DMT is a baseband implementation of more generalized OFDM and is most useful for channels with interference or strong low frequency noise resulting from artificial ambient light sources such as fluorescent and incandescent. The L-PAM and L-QAM systems (L is for multi-levels) normally provide high bandwidth efficiency at a reduced power efficiency. However, the L-pulse time modulation such as pulse position modulation (L-PPM) and digital pulse interval modulation (L-DPIM) can achieve higher power efficiency but at the expense of increased bandwidth requirement. The On-off-keying (OOK) scheme is the most widely used in free space optical (FSO) systems offers similar power requirement to 2-PPM, while passband modulation schemes such as binary phase shift key (BPSK) suffer from 1.8 dB power penalty. Therefore, a tradeoff between power and bandwidth requirements must be pursued^[5].

Selecting a modulation technique is a key factor that needs to be considered in communication system design. The proposed orthogonal frequency division multiplexing (OFDM) with interval shift key (ISK) for subcarrier modulation can provide balance between high bandwidth efficiency and high power efficiency.

INTERVAL SHIFT KEY (ISK)

Interval shift key (ISK) is a modulation technique that support pulse interval modulation and optical shift key. The ISK frame is structure based on pulse interval modulation frame. The header part

of the frame is a shift key modulation frame instead of a pulse frame. The ISK employs low spectral efficiency header to indicate high data rate represented by the interval part and hence improve spectral both and power efficiencies. Moreover, the ISK technique handles data in parallel form, i.e. data will be put in a group of bits based on type of pulse interval modulation used in the communication system.

The ISK technique is considered a counter based system that relies on mathematical and logical operations and datarate relies primary on processor speed rather on LED physical characteristics which true in traditional modulation techniques.

Interval Part

The interval is a decimal composition of number of bits (M bits) symbol represented by empty slots. Every M bits represented in a single symbol. Information is encoded by inserting empty slots between two adjacent headers. Every empty slot duration depends on sampling frequency. The number of empty slots is varying depending on decimal representation of M bits. The interval duration represented by the equation:

$$I(t) = L * S(t) \quad (1)$$

Where I(t) is interval duration, L is the decimal representation of the M bits symbol and S(t) is single slot duration.

Initially, the serial data stream will be converted to M bits parallel data, then the M bits data will be converted to its decimal equivalent and a counter will count intervals which equal to the decimal value. If the most significant bit (MSB) of the symbol is 1, the one's complement of the symbol will be modulated to reduce intervals (as in dual header pulse interval modulation DH-PIM) and header part will indicate that change. Moreover, if the next MSB is 1 then, the one's complement of the rest of the symbol (all bits except MSB) will be calculated.

The M value determines whether intervals time is short or long, hence it is prudent to select M value carefully. Table 1 shows a comparison between different M values and its impact on intervals length.

The minimum interval duration is calculated when all data are zeroes and the maximum value is calculated when all bits are ones except the first and second bits.

The average time required to transmit a group of bits is also an important factor when choosing M value. With small values of M, the header will be repeated multiple times therefore the duration of headers must be calculated carefully. Table2 shows the comparison between several M values and time required to transmit bits.

TABLE 1.M VALUES AND ITS EQUIVALENT NUMBERS OF INTERVAL SLOTS

M Value	Minimum Interval Length	Maximum Interval Length	Average Interval Length
4 bits	0	3	1.5
8 bits	0	63	31.5
16 bits	0	16383	8191.5
32 bits	0	10737418223	5368709110

From Table 1, the average interval slots are shortened when 'M' assumes low values. Unfortunately, when long stream of data need to be modulated with low 'M' values, the ISK frames will be repeated multiple times more than when high 'M' values are used. Hence, low bandwidth header will be repeated many folds which will affect the whole system data rate. To illustrate this scenario, assume that a 32 bits data stream needs to be modulated. The worst case interval length will occur when the interval matches maximum interval length. This leads to headers length of 200ns and sampling frequency of 1GHz was used as shown in Table 2. For various values of 'M', the ISK frame maximum and minimum duration required to modulate a 32 bits data stream is also presented in Table2.

TABLE 2.FRAMES DURATION REQUIRED TO MODULATE 32 BITS WITH DIFFERENT 'M' VALUES

M Value	Maximum frame duration (ns)	Minimum frame duration (ns)	Average frame duration (ns)
4 bits	1624	1600	1612
8 bits	1052	800	1452
16 bits	33166	400	16783
32 bits	10737418423	200	5368709310

From Table 2, when 'M' assumes small values the repetition of low bandwidth header causes increase in the frame length. Alternatively, when 'M' equals large value, the decimal equivalent will be a large number which leads to long intervals. For

example, for 'M' equals 8, the shortest frame duration achieved with of LED modulation bandwidth will be 5MHz and sampling frequency of 1 GHz.

Header Part:

The header part is the part that carrying the power of the signal. Actually it doesn't carry any information, it carries flags to represent how data in the interval was modulated and use these flags to recover the data in the demodulation process. Moreover, it preserves frame synchronization because every frame starts with a header. Headers carry 2 bits, each bit acts as a flag that reveals the modulated data characteristics in the interval as shown in Table3.

TABLE 3. HEADERS VALUES REPRESENTATIONS (WHERE \checkmark SYMBOL MEANS THE BITS SATISFY THE ITEM ABOVE)

Header Value	Data first bit is '1'	Data first bit is '0'	Data second bit is '1'	Data second bit is '0'
'00'		\checkmark		\checkmark
'01'		\checkmark	\checkmark	
'10'	\checkmark			\checkmark
'11'	\checkmark		\checkmark	

The first header bit determines whether the data bits were inverted in the modulation operation or not. If the first header bit equals '1' it indicates that the data MSB bit equals '1' and the data bits were inverted through logical inversion. Alternatively, if the first header bit equals '0' it shows that the data MSB bit is a '0' and that the data has not changed. This first header bit will be used to recover the data to its original format during demodulation process.

The second header bit determines whether the data bits excluding the MSB were inverted through logical inversion or not. If the second header bit equals '1', that means the second bit (bit after MSB) in data bits equals '1' and all data bits except the MSB were inverted through logical inversion. If thesecond bit in the header equals '0' that means the data bits didn't changed in the modulation operation.

HEADER MODULATION TECHNIQUE

The header modulation technique is crucial for high spectral and power efficiency of the ISK systems as well as performance in a noisy

environment. The header modulation technique must address the following factors:

- Data must be modulated in parallel form of 2 bit per frame.
- High power efficiency.
- High immunity to noise.
- Ability to use with multicarrier modulation.

It is prudent to investigate each of these techniques in more details as provided in the following section.

4-PAM:

The pulse amplitude modulation technique belongs to pulse amplitude level modulation scheme. It transmits more information per symbol through the channel at the cost of lower power efficiency. It is more sensitive to the channel nonlinearities as well as the noise. Fig.2 shows the behaviour of 4-PAM in the environment of adaptive white Gaussian noise (AWGN) channel.

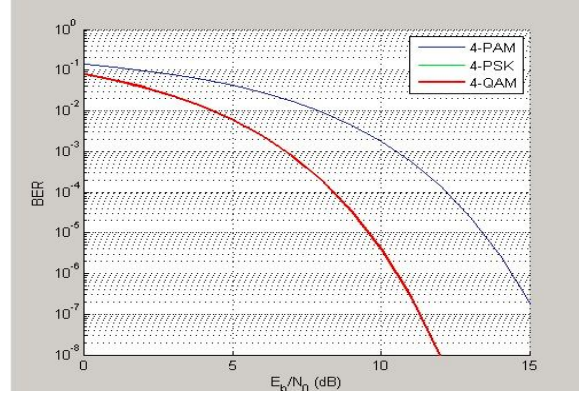


Figure2: 4-PAM, 4-PSK, and 4-QAM BER vsEb/N0 in AWGN Channel

The 4-PAM technique is a distorted modulation technique due to amplitude levels variation. Additionally, this technique is attributed with high power consumption resulting from use of high levels of direct current (DC). Therefore, the 4-PAM is not suitable to modulate the header of the ISK.

4-ASK:

In the amplitude shift key (ASK) data is modulated by varying the carrier amplitude. It transmits more information per symbol through the channel at the cost of lower power efficiency. This technique shares most of the characteristics of pulse amplitude modulation (PAM), hence it has low power efficiency, but higher immunity to the noise.

4-PSK:

A complex baseband M-PSK signal is represented by:

$$S_n(t) = \sqrt{\frac{2E}{T}} \cos(\omega t + \theta) \quad (2)$$

Where E is the symbol energy of each M-PSK symbol, T is the bit period, θ is the phase shift for each of the symbols. For 4-PSK M value equals 4.

In 4-PSK modulator, every 2 input data bits are mapped to one complex valued 4-PSK symbol. Each symbol is gray coded prior to mapping them to the 8-PSK constellation, this allows only one bit change in the constellation, thereby avoiding abrupt phase changes in the constellation which may lead to additional errors in the receiver. In 4-PSK there are four possible symbols that can be transmitted. Four different phases will be used to represent each 4-PSK symbol. Each symbol is 90° away from adjacent symbols. Figure 2 shows the behavior of 4-PSK in an environment with adaptive white Gaussian noise (AWGN) [7].

From Figure 2, the behaviour of 4-PSK in adaptive white Gaussian noise (AWGN) channel is better than 4-ASK due to lower BER rates.

4-QAM:

The M level quadrature amplitude modulation (M-QAM) is a generic modulation technique where the information is encoded into both the amplitude and phase of the sinusoidal carrier. It combines both M-ASK and M-PSK modulation techniques. M-QAM modulation technique is a two dimensional modulation technique and it requires two orthonormal basis functions.

The information signals are Gray coded in order to restrict the erroneous symbol decisions to single bit error, the adjacent symbols in the transmitter constellation should not differ more than one bit. Usually, the grey coded symbols are separated into phase and quadrature bits and then mapped to M-QAM constellation. The rectangular configuration of QAM makes it easier to consolidate the previously mentioned steps into a simplified Look-Up-Table (LUT) approach [8].

From Figure 2, it can be noted that 4-QAM and 4-PSK have better behaviour in adaptive white Gaussian noise channel than other modulation techniques when compared to 4-PAM. Also, Fig.2 shows The 4-QAM and 4-PSK modulation techniques show similar BER performance, however, the 4-PSK uses fixed amplitude

compared with 4-QAM. Therefore, the 4-PSK modulation consumes less power than the 4-QAM system. Consequently, the 4-PSK will be a better choice for header modulation in the ISK frame.

INTERVAL SHIFTKEY FRAME CONSTRUCTION

The interval shift key (ISK) modulation depends primarily on mathematical and logical operations to construct the frame. Hence, the processor frequency is the main parameter that impact the data rate. The LED physical characteristics have virtually no impact on the data rate unlike in traditional modulation techniques. The flowchart of processes involved in the ISK modulator is shown in Figure 3.

Modulation Operation:

The ISK modulator reads serial 8 bits of data from the data source and converts to parallel format. These parallel bits represent the data symbol which will be modulated in the interval (I) part. If the MSB of the 8 bits symbol equals '1', all the interval value will be inverted logical inversion in order to reduce interval decimal value and header (H) part will indicate this change by putting a '1' in the header MSB bit. Otherwise, if the symbol MSB equals '0', interval value will remain the same and header second bit value will be set to '0'.

If the second data bit (bit after the MSB) of the 8 bits data symbol equals '1', all of the symbol bits except the first bit (MSB) will be inverted logical inversion and header (H) will indicate this change by putting a '1' value in the header least significant bit (LSB). Alternatively, if the symbol next MSB equals '0', (I) will remain the same and the header LSB bit value will set to '0'.

The next step will be to convert the interval (I) value its decimal equivalent and the counter will count empty interval slots which equals to the decimal value of I follows 4-QAM frame loaded by H value. The ISK frame defines as:

$$f(t) = \begin{cases} \sqrt{\frac{2E}{T}} \cos(\omega t + \theta) & t = t(H) \\ 0, & t = t(I) \end{cases} \quad (3)$$

Where $f(t)$ is ISK signal, T is PSK frame duration, $t(H)$ is header time, and $t(I)$ is the interval time.

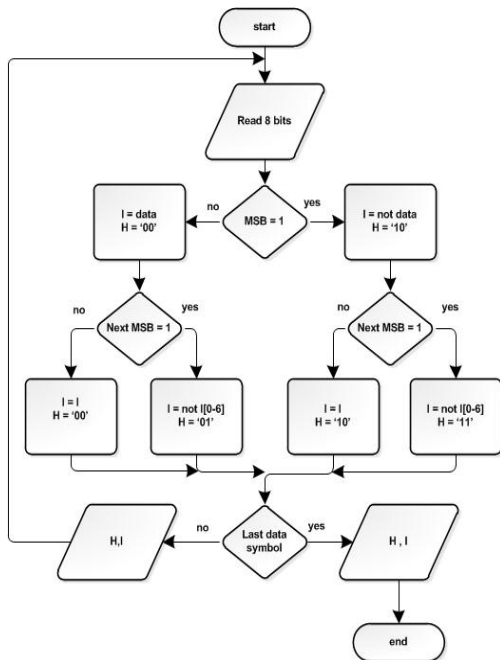


Figure 3: The ISK modulation operation flow chart where H is header and I is interval

Demodulation Operation:

The demodulation operation used to extract bits stream data from ISK frame in the receiver side. The flow chart of demodulation steps are shown in Figure 4. In the demodulation operation, interval slots are used to determine the frame decimal value by counting empty slots in the frame. The header value is used to determine the status of the I value whether it was inverted or not in the modulation operation and counts how many times it was inverted. This is necessary to translate interval value to it is origin. Moreover, it keeps synchronization of the frames.

Initially, the demodulator receives an ISK frame consists of a header and an interval. Then, the demodulator separates the header and the interval. If the header (H) equals '1X' (X symbol represents a don't care state) that means the interval value was inverted in modulation operation. Then the interval (I) will be inverted logical inversion. Alternatively, if H equals '0X', that means the interval MSB equals '0' and interval was not inverted in modulation operation, hence the interval will remain the same.

Next, the demodulator will test the next bit (LSB) of H. If H equals 'X1' that means interval was inverted in the second level inversion. Therefore, all bits of I will be inverted logical inversion except the MSB. If H equals 'X0', I value will remain unchanged. Then, (I) binary value will represent the received data.

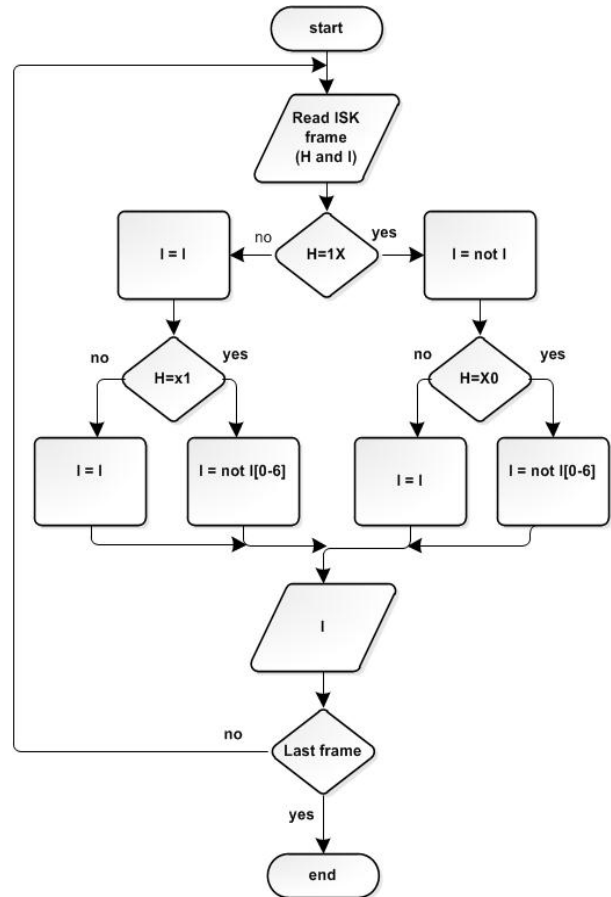


Figure 4: The ISK demodulation operation flow chart where X means don't care

ISK INMULTICARRIER MODULATION

Multicarrier modulation is a technique used to transmit multiple signals in parallel. This technique is used to overcome the frequency selectivity of the wideband channel experienced by single-carrier transmission. Multiple carriers can be used for high rate data transmission [9].

Orthogonal Frequency Division Multiplexing (OFDM):

The orthogonal frequency division multiplexing is a special case of multicarrier transmission, when a single data stream is transmitted over a number of lower rate subcarriers.

The idea used in OFDM is to use parallel data and frequency division multiplexing (FDM) with overlapping subchannels to avoid multipath distortion, as well as to fully use the available bandwidth. Figure 5 illustrates the difference between the conventional nonoverlapping multicarrier technique and the overlapping multicarrier modulation technique.

As shown in Figure 5 by using the overlapping multicarrier modulation technique, almost 50% of bandwidth is saved. To realize the overlapping multicarrier technique, however crosstalk between subcarriers must be reduced, which means that the orthogonality between subcarrier must be used^[10].

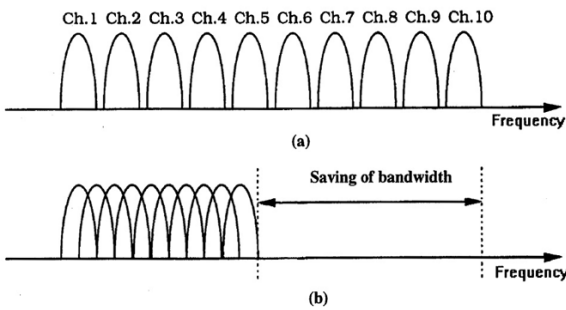


Figure 5: The Concept of OFDM Signal: a. Conventional Multicarrier Technique, b. Orthogonal Multicarrier Technique [10].

OFDM Principles

The basic principle of OFDM is to split a high rate data stream into a number of lower rate streams which are transmitted simultaneously over a number of subcarriers. Because the symbol duration increases for lower rate parallel subcarriers, the relative amount of dispersion in time caused by multipath delay spread is decreased. Inter-symbol interference is eliminated almost completely by introducing a guard time in every OFDM symbol. In the guard time, the OFDM symbol is cyclically extended to avoid inter-carrier interference. Each subcarrier has exactly an integer number of cycles in the OFDM symbol interval and the number of cycles between adjacent subcarrier differs by exactly one. This property accounts for the orthogonality between the subcarriers^[10].

The complex baseband of OFDM signal is nothing more than an inverse Fourier transform of N 's sinusoid input symbols. Equations 5, 6 show discrete Fourier transform (DFT) and an inverse discrete Fourier transform (IDFT) respectively.

$$X[k] = \sum_{n=1}^N X(n) e^{-\frac{j2\pi nk}{N}} \quad (4)$$

$$X[n] = \frac{1}{N} \sum_{k=1}^N X(k) e^{\frac{j2\pi nk}{N}} \quad (5)$$

Where k is frequency index, n is time index, N is the number of harmonics.

This transform can be implemented efficiently using fast Fourier transform (FFT) and inverse fast Fourier transform (IFFT). An N point IDFT requires a total of N^2 complex multiplications which are actually on phase rotation. There are also additions necessary to do an IDFT, but since the hardware complexity of an adder significantly lower than that of a multiplier or phase rotator, The IFFT drastically reduces the amount of calculations by exploiting the regularity of the operation in the IDFT. Using the radix-2 algorithm, an N -point IFFT requires only $\frac{1}{2} \log_2 N$ complex multiplications^{[10], [11]}.

OFDM with ISK Subcarriers:

In order to achieve higher data rate ISK modulation need to be tested using orthogonal frequency division multiplexing. This can be achieved by using inverse fast Fourier transform (IFFT). But according to ISK frame construction, there are some constraints which can affect the orthogonality of the subcarriers. One solution is that, the first subcarrier must be a pilot subcarrier which does not carry any information. It only determines the length of the OFDM signal. The empty slots must be less than half of the first subcarrier cycle which reduces the risk of impacting the orthogonality. The empty slots will be modulated as zero padding.

If a LED bandwidth of about 6.4MHz is used with 64 subcarriers, 52 can be allotted for data and 12 can be used as pilot subcarriers. The first subcarrier frequency is 100 kHz, and the last subcarrier frequency is 6.4MHz. To make interval part less than half a cycle of the first subcarrier, the single interval slot should take a maximum period of about 5×10^{-6} sec. This means that the minimum sampling frequency is 6MHz. But according to Shannon theory, the sampling frequency must be more than or equals 12.8 MHz which doesn't affect the ISK conditions.

Optical Wireless OFDM Signal:

In optical wireless communication, intensity modulation with direct detection (IM/DD) technique is used for data transmission. However, in IM/DD communication, the phase of the optical carrier cannot be used to transmit information and transmitted signal must be real and positive. These additional constraints require some special care if the OFDM is to be used in optical wireless communications since the equivalent baseband time-domain OFDM signal is usually complex.

The most common technique to generate a real time-domain signal is to preserve the Hermitian symmetry property of the OFDM subcarriers at the expense of losing half of the available bandwidth. Although this technique produces a real time domain signal, this signal is bipolar and needs to be converted into unipolar signal before the transmission^[12].

There are multiple techniques to produce unipolar and positive OFDM signal includes Asymmetric Clipped Optical OFDM (ACO-OFDM), Flip-OFDM and Spectrally Factorized Optical (SFO) OFDM. But all techniques mentioned before suffer from either losing of half bandwidth or high hardware complexity.

The technique was used in this demonstration to keep signal unipolar and positive is called DC offset optical OFDM (DCO-OFDM). The DCO-OFDM is the simplest way to make signal unipolar and positive and doesn't reduce spectral efficiency. So, the spectral efficiency of ACO-OFDM is only one-half that of DCO-OFDM. This is true because only the odd subcarriers are data carrying in ACO-OFDM while all subcarriers are data carrying in DC-OFDM.

The DC-OFDM has other advantages such as providing the right level of lighting/illumination in the case of visible light communications, permit the full swing of the input signal, and ensure that the signal is kept as much as possible within the linear region of the LED characteristics curve.

The process of making the signal real and positive is highlighted in the following steps:

- Hermitian symmetry is imposed on the complex signal that feeds into the IFFT block. This ensures that the output of the IFFT block is real.
- A DC is then added to obtain a unipolar signal, resulting in what is termed DC – optical – OFDM (DCO-OFDM).

An alternative approach is to use asymmetrically clipped OFDM (ACO-OFDM). In ACOOFDM, no DC is added. The bipolar real OFDM signal is clipped at the zero level. That is, the entire negative signal is removed. It turns out that if only the odd-frequency OFDM subcarriers are nonzero at the IFFT input, the noise caused by clipping affects only the even subcarrier and the data carrying odd subcarriers are not impaired at all.

MATLAB SIMULATION

In order to develop the modulator and demodulator of an OFDM system with ISK subcarriers, MATLAB R2013a is used.

Transmitter Side:

Firstly, Binary serial data is created using 'randi' function. Randi function uniformly distributed pseudorandom integers. With the syntax `b = randi([iminimax],m,n)`. It returns a data stream matrix with minimum value of `imin` (in this case it is '0') and maximum value of `imax` (in this case it is '1'). The number of rows equals `m` and the number of columns equals `n`. `M` will equal 1 and `n` will equal the number of bits^[6].

The ISK modulator deals with data in a parallel form. So data need to be converted to data symbols each symbol consists of 8 parallel bits. So, in order to convert serial data bits to parallel reshape function is used. The syntax of reshape function is `B = reshape(A,m,n)`. It returns the `m`-by-`n` matrix `B` whose elements are taken column-wise from `A`. In this case, `B` is the matrix that contains data symbols each symbol consists of 8 bits. `A` is the serial bit stream matrix, `m` is the number of symbols (number of symbols = number of bits/8) and `n` equals 8^[6].

After convert data to parallel form, header and interval will be calculated for every symbol depending on its value as mentioned before.

Header will be generated using 4-PSK modulation using `pskmod` function. The syntax of `pskmod` function is `y = pskmod(x,M)`. The output is complex envelope `y` of the modulation of the message signal `x` using phase shift keying. `M` is the alphabet size and must be an integer power of 2. The message signal must consist of integers between 0 and `M-1`. So `bi2de` is used to convert header to decimal value.

`D= bi2de(b)` converts a binary row vector `b` to a nonnegative decimal integer. Each row is interpreted separately as a binary number. In this

case, the output d is a column vector, each element of which is the decimal representation of the corresponding row of b .

Interval is calculated using mathematical and logical operations as mentioned before. Interval is converted to decimal value to apply mathematical operation using `bi2de` function [6].

In order to create OFDM carrier, ISK symbols need to be converted to parallel form. Each parallel symbol set contains number of ISK symbols equals to number of subcarriers. 52 data subcarrier are used in this simulation. This operation manipulated using `reshape` function.

The pilot signals are used for tracking frequency offset and phase noise. In matlab the subcarrier matrix will be converted to columns and pilot subcarriers will be inserted as columns insertion.

An inverse fast Fourier transform converts the frequency domain data stream into the corresponding time domain. The function $y = \text{ifft}(X)$ returns the inverse discrete Fourier transform (DFT) of vector X , computed with a fast Fourier transform (FFT) algorithm. `ifft` returns the inverse DFT of each column of the matrix. `ifft` tests X to see whether vectors in X along the active dimension are conjugate symmetric. An N -element vector x is conjugate symmetric $x(i) = \text{conj}(x(\text{mod}(N-i+1, N)+1))$ for each element of x .

Also $Y = \text{fftshift}(X)$ is used to rearrange the outputs of `ifft` by moving the zero-frequency component to the center of the array. It is useful for visualizing a Fourier transform with the zero-frequency component in the middle of the spectrum. For vectors, `fftshift(X)` swaps the left and right halves of X . For matrices, `fftshift(X)` swaps the first quadrant with the third and the second quadrant with the fourth [6].

In an OFDM transmission, it known that the transmission of cyclic prefix does not carry ‘extra’ information, it copies the front of the symbol to the empty slot between consecutive OFDM symbols. This operation can be done on matlab by adding columns to OFDM matrix.

Receiver Side:

After receiving the OFDM signal, cyclic prefix will simply be removed by removing the extra columns that was added in the modulator.

The fast Fourier transform converts time domain signal to frequency domain. This can be

done using `fft(x)` function in matlab. The operation is similar to the `ifft(x)` function, and the pilot signals also can be removed simply by subtract pilot columns. Then, the data will be demodulated using ISK demodulator and data will be converted to serial form using `reshape` function.

RESULTS AND DISCUSSIONS

The ISK performance is evaluated in term of power efficiency and bandwidth efficiency and compared with other modulation techniques used in optical wireless communication. MATLAB R2013a is used to simulate the systems in the condition of Adaptive White Gaussian Noise channel (AWGN).

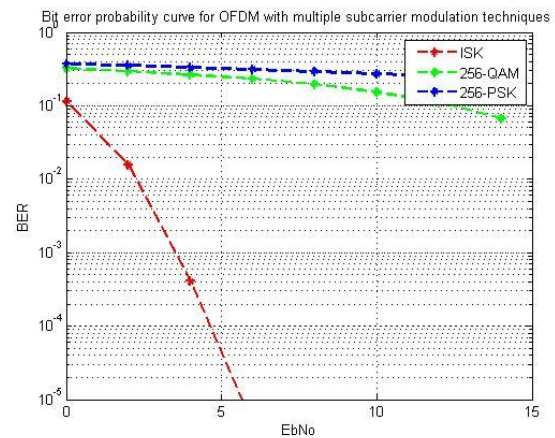


Figure 6: The performance of ISK with OFDM in the AWGN channel compared with other modulation schemes.

Power efficiency is the most important factor when evaluating modulation technique suitable for indoor optical wireless communication system. In this demonstration modulation scheme offers a certain optical average power and therefore they are compared in term of average power required to achieve desired BER performance of signal to noise ratio (SNR). The power efficiency of a modulation scheme given by average power required to achieve a given BER at a given data rate [5], [13]. Figure 6 shows the performance of ISK with OFDM in the AWGN channel compared with other modulation schemes.

Figure 6 depicts that the OFDM with 256-QAM and 256-PSK subcarriers have high spectral efficiency but these modulation techniques could not be used due to distortion associated with these modulation techniques. Moreover, results show that the OFDM with ISK subcarriers have the best

BER performance in AWGN channel which reduce the power consumption.

Although the optical carriers can be theoretically considered as having an unlimited bandwidth the constraints like LED capacitance and channel capacity limit the amount of bandwidth that is practically available^[5].

The bandwidth efficiency was calculated in term of spectral efficiency. The ISK in OFDM system with 64 subcarriers (52 subcarriers used for data) recorded spectral efficiency of 416 bit/Hz. Figure 7 shows a comparison between multiple modulation techniques in term of bandwidth efficiency.

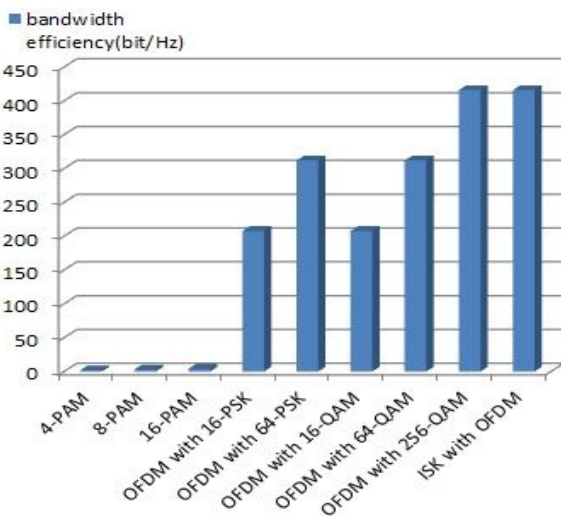


Figure 7: Bandwidth efficiency of multiple modulation techniques.

The system complexity is measured as a number of calculations. The ISK system requires additional 5 logical operations and calculations equal to interval value in addition to OFDM calculations. So ISK system is more complex than normal OFDM system.

CONCLUSION

The bandwidth efficiency and power efficiency are the most important factors for any communication system design. In optical wireless communication there are various methods developed to raise bandwidth efficiency and power efficiency. These include increasing the number of carrier in a multicarrier modulation, design high bandwidth LED, use optical filter, and electronic filters. The ISK modulation technique is simulated for bandwidth efficiency and power efficiency of optical wireless communication. It is used to modulate subcarriers in OFDM and was shown

that it can be used beside all techniques mentioned above. ISK technique depends on processor performance to increase data rate rather than LED bandwidth as in traditional modulation techniques. Simulated results reveals that an ISK with OFDM recorded very high spectral efficiency of about 416 bit/Hz in condition of 52 data subcarriers. ISK has very low BER and power consumption compared to other modulation techniques because of empty slots in interval which reduces the power consumption and increase system reliability. ISK also may be used in RF channels which will improve the performance of communication systems in term of power efficiency and bandwidth efficiency.

Since ISK data rate depends on how fast processor can count the intervals, the main drawback of the ISK is huge number of calculation. Modern processor designs are enabled with fast processing speed, than that of the LED's, this drawback will not affect the use of ISK. The presented results are based on simulation work. Realistic measurements of systems with ISK in term of power consumption, transmission range, multipath dispersion and hardware noise will be required as an extension of this work.

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