Multilevel Dual Header Pulse Interval Modulation Scheme for Optical Wireless Communications

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***Abstract*—Digital modulations provide data to be sent by the optical link. In addition, digital modulation acts like an encoder. Digital modulations encrypt the data and are useful for unsecured channels and in applications where security is very important to us (such as military applications). This paper presents the Multilevel Dual Header-Pulse Interval Modulation (MDH-PIM) scheme for optical wireless communications. MDH-PIM is an isochronous scheme and uses this capability to synchronize the modulated frames. Theoretical and simulation results indicate the better transmission rate of data, bandwidth requirement and transmission power of the MDH-PIM modulation than the Dual Header Pulse Interval Modulation (DH-PIM) and Digital Pulse Interval Modulation (DPIM) schemes. Error rate analysis shows that MDH-PIM offers better packet error rate performance than On-Off Keying (OOK) dose, but it is marginally inferior as compared with DH-PIM.**

***Index Terms*—FSO communication, Modulation, OOK, DPIM, DH-PIM, MDH-PIM**

I. Introduction

Wireless telecommunication systems appear in radio and optical systems. Both these systems are low cost and reliable in terms of security. Moreover, these systems have high data transmission rates and need low power in point-to-point communications and network communications in closed environments. However, features such as wide bandwidth, high data transmission rates, high security, low power consumption, low cost and rapid expansion have led wireless optical systems to be used more than wireless radio systems [1], [2]. Optical wireless systems have other advantages such as their lack of influence from electromagnetic waves, their no need to obtain permission from the FCC to allocate frequencies, and most importantly, their capability to be limited in a particular location, so that two identical optical systems can be used in two adjacent rooms without interfering with each other [2], [3]. In addition, in multimedia and military applications, we need very high data transmission rates and low power consumption; these are the reasons why wireless optical communication systems are used more in the military industry.

One type of optical links is the diffused link in which the optical signal reflects to reach the receiver after colliding with the wall and ceiling of the room or the objects in the room. Most optical links are of the diffused type because there is no requirement that the optical transmitters and receivers face each other and therefore there is no requirement of alignment between them [1], [4]. Since the optical signal takes a long path to reach the receiver in the diffused link, it weakens the optical signals, depending on the physical parameters of the room, including its size, positions of the transmitter and the receiver relative to each other, the furniture, etc. [5], [6].

In addition, optical signals are very sensitive to the optical noise of the environment. In addition, multi-path propagation of optical signals creates interference in optical symbols. In order to overcome the above problems, we need transmitters that have the power to transmit the optimal signal. On the other hand, we face some constraints in relation to the increased power of optical transmitters, since such an increase can damage the human skin and eyes. Also, in applications where there is a possibility of transmission, the power consumption should be minimized so that the lifetime of the device can be increased, so the increased power consumption of optical transmitters creates restrictions on their transmission. Therefore, in order to make the optical signal sufficiently high and simultaneously reduce the power consumption of optical transmitters, we use modulation techniques to maximize the ratio of maximum power to the mean power of the optical signal [1], [5], [7]. In fact, digital modulations prepare information to be sent by free space optical links.

Fig. 1 shows the block diagram of the transmitter and receiver of a wireless optical system. Here, the M-bit is selected from the input signal, and after modulation, a digital signal appears at the output of the modulator. An optical source is launched by the light transmitter, and the modulated signal propagates as light in free space. An optical wireless signal propagated in free space is

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accompanied with a communication channel noise that is a kind of shot noise created by the background light. This noise model is modeled as the additive white Gaussian noise. Optical symbols also interfere in intrusion systems due to the presence of multi-path channels, particularly at speeds greater than 10Mbps [8], [9].

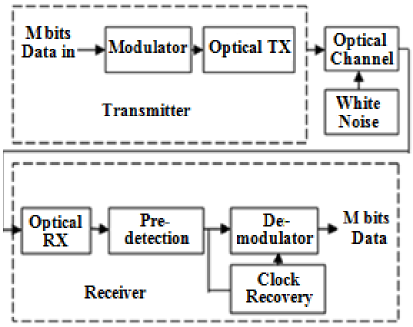

Fig. 1. The block diagram of the transmitter and receiver of a wireless optical system.

In the optical receiver the Positive Intrinsic Negative (PIN) or Avalanche Photo Diode (APD) optimal detector converts the received signal into an equivalent electrical signal. The detected signal then passes through a filter and the filter output enters the demodulator. The demodulator extracts the main information. It should be noted that the Clock Recovery block is used for the transmitter and receiver synchronization.

Digital modulations will also be useful from another perspective. In this type of modulation, digital information enters the modulator and another code appears in the output of the modulator. In fact, the modulator appears as a coder and modulation is considered a kind of encryption [10]. As we know, one way to create passive defense to prevent data loss and ensure their security against attackers is to use encoders to encrypt information. The use of digital modulations, in addition to the above-mentioned advantages, can create passive defense in the transmission of information. Therefore, the use of such modules in environments with low security of transmission increases the security of data transmission.

The modulation operation in these modulations is done in such a way that multi-bit digital data is entered into the modulator and a code that is longer than the first data and most importantly contains a "one" bit along with a number of "zero" bits appears in the output. In other words, the number of "one" bits in the output of the modulator is reduced, which increases the security of the data transmission, since noise and external factors affect the "one" bits more than the "zero" ones. Therefore, these modulations increase the security in data transmission by decreasing the number of "one" bits and increasing the time spent for sending the output bits.

Several types of digital modulations are used in optical wireless communications. The most important of these modulations are On-Off Keying (OOK), Pulse Position Modulation (PPM), Digital Pulse Interval Modulation (DPIM), Modified Digital Pulse Interval Modulation (MDPIM) and Dual Header Pulse Interval Modulation (DH-PIM) [1], [11], [12]. DPIM modulation has been a good alternative to OOK and PPM modulations in the last decade. Although PPM modulation outperforms DPIM modulation and has greater power efficiency than it, it needs greater bandwidth and has less transmission capacity than the DPIM modulation [10]. The implementation of DPIM modulation is very complicated because the length of the modulated symbols is variable. However, DPIM modulation offers more transmission capacity by deleting slots that are left unused in PPM modulation [1], [13]. The use of the optimized modulation of DPIM or the MDPIM modulation has removed the problem of DPIM modulation implementation, but the data transmission capacity is reduced due to the use of MDPIM modulation [12]. After MDPIM modulation, DH-PIM modulation has been proposed. The DH-PIM modulation has the ability to synchronize slots and frames. In addition, this modulation has more data transmission capacity and requires less bandwidth than PPM, DPIM and MDPIM modulation [14], [15].

We present the Multilevel Dual Header-Pulse Interval Modulation (MDH-PIM) in this paper. This modulation has a higher transmission rate than other modulations and requires less bandwidth. In addition, it has higher transmission power than other modulations. The two parameters of error and power needed to perform the modulation are greater in the MDH-PIM modulation than the DH-PIM modulation, which can be reduced by changing the values of M and α in the MDH-PIM modulation so that the error and power required to perform the MDH-PIM modulation becomes less than the DH-PIM modulation. Another advantage of the MDH-PIM modulation is its easier implementation than the DH-PIM modulation.

The sections of this article are organized as follows: The second section presents the DH-PIM modulation and the third section presents the proposed modulation of MDH-PIM. Section 4 compares the parameters of digital modulations. The fifth section presents the conclusion part and the final section presents the references.

II. DH-PIM Modulation Structure

Since the proposed modulation of MDH-PIM is the optimized version of the DH-PIM modulation, this section introduces the DH-PIM modulation. With the DH-PIM modulation, an M-bit input symbol of the OOK signal is mapped to a frame. The nth frame (S_n (h_n, d_n)) in a DH-PIM sequence consists of a header (h_n) that starts the frame and the information slots (d_n) [14], [15] (Fig. 2).

With respect to the bit with the most significant bit (MSB) value of the input symbol, we have two different headers of H_1 and H_2, corresponding to MSB=0 and MSB=1 respectively, respectively. H_1 and H_2 have a length equal to $T_h=(\alpha+1)T_s$, where α represents a positive integer and T_s represents the length of each slot and consists of a pulse and a protective band. The pulse lengths of H_1 and H_2 are $(\alpha T_s)/2$ and αT_s respectively. After the pulse, there is a protective band with the length of $T_g \varepsilon\{(0.5\alpha+1)T_s, T_s\}$, related to H_1 and H_2 respectively and this protective band prevents from the co-occurrence of two pulses (When the input symbol is equal to decimal zero). The data section includes d_n slot of zero. When the modulated frame starts with H_1, the number of zero slots is equal to the decimal value of the input symbol, which varies from zero to $2^{M-1}-1$. When the modulated frame starts with H_2 the number of zero slots is equal to the decimal value of the input symbol. It should be noted that the pulse header is a time reference separating the previous and next symbols from each other and uses this property to synchronize the frames [10].

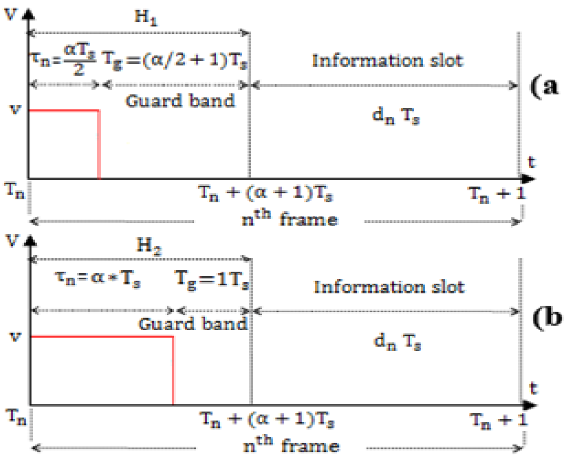

Fig. 2. The *n*th symbol of DH-PIM a) Header 1 (H_1), b) Header 2 (H_2).

Throughout this paper we show the DH-PIM modulation with L–DH–PIM$_\alpha$, in which $L=2^M$. Based on the values of L and α, 8–DH–PIM$_1$ and 8–DH–PIM$_2$ refer to DH-PIM with (M=3, $L=2^M$=8) and α=1.2 respectively. Like the DH-PIM modulation, we display DPIM and PPM modulations with L-DPIM and L-PPM.

As observed in the DH-PIM modulation structure, the DH-PIM modulation not only eliminates the zero slots appearing after each pulse in the PPM modulation, it also reduces the average length of the symbols compared to the DPIM, thereby increasing the data transmission capacity. The minimum, maximum and average lengths of the modulated frame and the length of the slot in the DH-PIM modulation are as follows [15]:

$$L_{\min} = \alpha + 1 \tag{1}$$

$$L_{\max} = 2^{M-1} + \alpha \tag{2}$$

$$L_{avg} = \frac{2^{M-1} + 2\alpha + 1}{2} \tag{3}$$

$$T_s = \frac{2M}{(2^{M-1} + 2\alpha + 1)R_b} \tag{4}$$

where R_b represents the input data transmission rate.

III. The Proposed MDH-PIM Modulation

Like the DH-PIM modulation in the transmitter, an M-bit symbol of the OOK signal is mapped to a frame onto the information in order to perform the MDH-PIM modulation. The n_{th} frame $S_n(h_n, d_n)$ in a MDH-PIM sequence contains a header (h_n) and information slots (d_n). Considering the bit with MSB value and the previous bit with past most significant bit (PMSB) value of the input word, we have four different headers H_1, H_2, H_3, and H_4, respectively, which are related to PMSB=0, MSB=0, PMSB=1, and MSB=0, PMSB=0 and MSB=1, PMSB=1, and MSB=1 respectively. For example, these states for M=4 are shown in Fig. 3.

So, we will have one of the following four states for the MDH-PIM modulation, depending on the MSB and PMSB values of the input information.

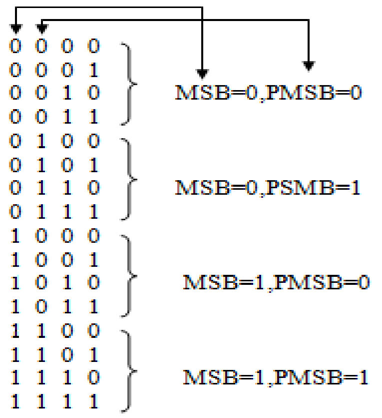

Fig. 3. Various states of the input data for M = 4 in the MDH-PIM modulation.

A. *First State (MSB=0 and PMSB = 0)*

If the MSB and PMSB of the input symbols are zero, then H_1 header will be used, which consists of a pulse with a range of A and length $(\alpha T_s)/2$ and a protective band of length $((\alpha/2+1)T_s$, where α represents a positive integer and T_s represents the length of a slot. The zero slot is put in the information part equal to the decimal value of the input symbol (without taking into account the two bits of MSB and PMSB) (Fig. 4).

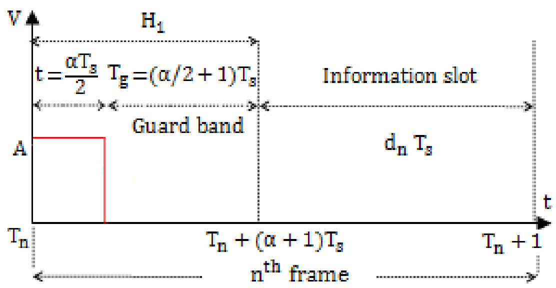

Fig. 4. MDH-PIM modulation when MSB = 0 and PMSB = 0.

B. *Second State (MSB=0 and PMSB = 1)*

If the MSB of the input symbol is zero and the PMSB is equal to one, then H_2 header will be used, which consists of a pulse with a range of 2A and length $(\alpha T_s)/2$ and a protective band of length $((\alpha/2+1)T_s$, where α represents a positive integer and T_s represents the length of a slot. The zero slot is put in the information part equal to the decimal value of the input symbol (without taking into account the two bits of MSB and PMSB) (Fig. 5).

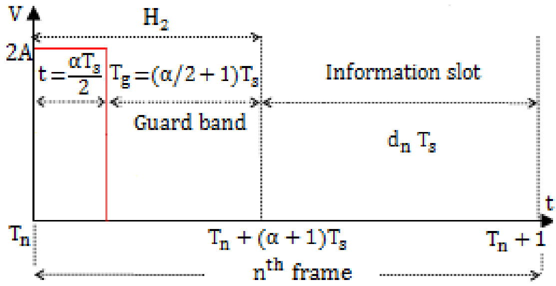

Fig. 5. MDH-PIM modulation when MSB = 0 and PMSB = 1.

C. *Third State (MSB=1 and PMSB = 0)*

If the MSB of the input symbol is one and the PMSB is zero, then H_3 header will be used, which consists of a pulse with a range of A and length αT_s and a protective band of length $1T_s$. The zero slot is put in the information part equal to the decimal value of the input symbol (without taking into account the two bits of MSB and PMSB) (Fig. 6).

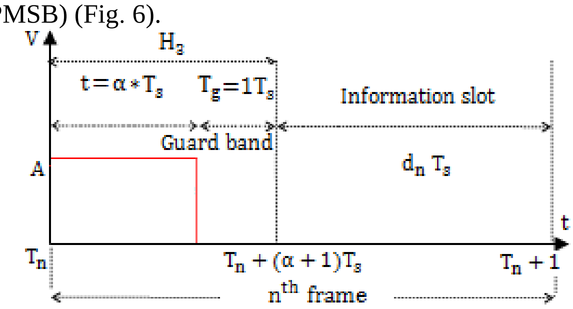

Fig. 6. MDH-PIM modulation when MSB = 1 and PMSB = 0.

D. *Fourth state (MSB=1 and PMSB = 1)*

If the MSB and PMSB of the input symbols are equal to one, then H_4 header will be used, which consists of a pulse with a range of 2A and length αT_s and a protective band of length $1T_s$. The zero slot is put in the information part equal to the decimal value of the input symbol (without taking into account the two bits of MSB and PMSB) (Fig. 7).

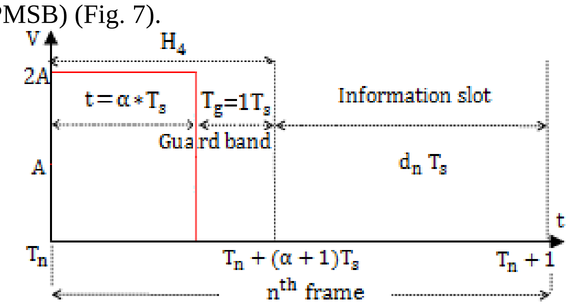

Fig. 7. MDH-PIM modulation when MSB = 1 and PMSB = 1.

As shown in Fig. 4 to Fig. 7, the pulse header is a time reference separating the previous and next symbols and using this property to synchronize the frames. The MDH-PIM modulation not only eliminates the empty slots that appear after each pulse in the PPM modulation, but also reduces the length of the modulated frames by half the DH-PIM modulation and more than 1/6 length of the PPM modulation frames, thereby increasing the speed of data transmission and reducing the required bandwidth. Table I shows the OOK, PPM, DPIM, DH-PIM2 and MDH-PIM2 modulations for M = 4.

TABLE I. 16-PPM, 16-DPIM, 16-DH-PIM2 AND 16-MDH-PIM2 MODULATIONS FOR FOUR-BIT OOK DATA

OOK	**16-PPM**	**16-DPIM**
0000	1000000000000000	10
0001	0100000000000000	100
0010	0010000000000000	1000
0011	0001000000000000	10000
0100	0000100000000000	100000
0101	0000010000000000	1000000
0110	0000001000000000	10000000
0111	0000000100000000	100000000
1000	0000000010000000	1000000000
1001	0000000001000000	10000000000
1010	0000000000100000	100000000000
1011	0000000000010000	1000000000000
1100	0000000000001000	10000000000000
1101	0000000000000100	100000000000000
1110	0000000000000010	1000000000000000
1111	0000000000000001	10000000000000000
OOK	**16-DH-PIM$_2$**	**16-MDH-PIM$_2$**
0000	100	100
0001	1000	1000
0010	10000	10000
0011	100000	100000
0100	1000000	200
0101	10000000	2000
0110	100000000	20000
0111	1000000000	200000
1000	1100000000	110
1001	110000000	1100
1010	11000000	11000
1011	1100000	110000
1100	110000	220
1101	11000	2200
1110	1100	22000
1111	110	220000

As shown in Table I, the data transmission capacity increases in the MDH-PIM modulation, since it eliminates the empty slots that appear after each pulse in the PPM modulation. It also reduces the length of modulated symbols as compared to the DPIM and DH-PM modulations.

The minimum, maximum and average lengths of modulated symbols in the MDH-PIM are as follows:

$$L_{\min} = \alpha + 1 \tag{5}$$

$$L_{\max} = 2^{M-2} + \alpha \tag{6}$$

$$L_{avg} = \frac{2^{M-2} + 2\alpha + 1}{2} \tag{7}$$

$$T_s = \frac{2M}{(2^{M-2} + 2\alpha + 1)R_b}\alpha + 1 \tag{8}$$

As the above equations show, the average length of the output symbols in the MDH-PIM modulation is much less than that in the PPM, DPIM and DH-PIM modulations, and this property is more evident for M> 6. (1/6 average length of PPM, 1/3 average length of DPIM and 1/2 average length of DH-PIM)

IV. COMPARISON OF DIGITAL MODULATION PARAMETERS

In this section, we compare digital modulations in terms of bandwidth required for modulation, transmission rate (transmission capacity), average transmission power, error performance, and power required to perform modulation.

A. Bandwidth Required for Modulation

In order to increase the amount of power received in optical receivers, we need high-level detectors, but increasing the level of the detector will cause restrictions in the bandwidth of the receiver [16]. Therefore, one of the important parameters in the telecommunication systems is the bandwidth required by the transmitter and receiver. We prefer that the transmitter and receiver need less bandwidth.

Suppose that the transmitter sends the information at a rate of R_b bits per second. Therefore, the length of sending a bit is equal to [11], [17]:

$$T_s = 1/R_b \tag{9}$$

In digital telecommunication systems, bandwidth is defined as the reverse of the width of each pulse. As a result, the bandwidth required for the OOK modulation, $\mathrm{BW_{OOK}}$, is equal to [11]

$$\mathrm{BW_{OOK}} = 1/T_s = R_b \tag{10}$$

The PPM modulator selects M bits of input data and maps them onto the L-slot. Therefore, the length of a slot is equal to [18]:

$$T_s = M/(LR_b) \tag{11}$$

As a result, the bandwidth required for the PPM modulation, $\mathrm{BW_{PPM}}$, is equal to [11]:

$$\mathrm{BW_{PPM}} = \frac{1}{T_s} = \frac{L}{M} R_b = \frac{L}{M} \mathrm{BW_{OOK}} \tag{12}$$

As we expected, it is observed that the bandwidth in the PPM modulation has increased by *L*/*M* as compared to the OOK modulation.

In the DPIM modulation, if the time of each slot (T_s) is selected in such a way that sending the average length of the modulated symbols takes as long as sending of the M bit by the OOK modulation, In this case we have [19]

$$\frac{L+2g+1}{2} T_s = T_{M,\,\mathrm{OOK}} \tag{13}$$

In this case, the bandwidth of the DPIM modulation will be equal to [11], [19]:

$$\mathrm{BW_{DPIM}} = \frac{L+2g+1}{2M} R_b = \frac{L+2g+1}{2M} \mathrm{BW_{OOK}} \tag{14}$$

Therefore, the bandwidth of the DPIM modulation has decreased by about half as much as that of the PPM modulation. In this way, we can obtain the bandwidth required for DH-PIM and MDH-PIM modulations. So we have

$$\mathrm{BW_{DH\text{-}PIM}} = \frac{1}{0.5\alpha T_s} = \frac{2^{M-1}+2\alpha+1}{\alpha M} \mathrm{BW_{OOK}} \tag{15}$$

As the above equation shows, the bandwidth required for the DH-PIM modulation is lower than the bandwidth required for the DPIM modulation, and this value is also reduced when α increases [14], [20]. For the MDH-PIM modulation, we have

$$\mathrm{BW_{MDH\text{-}PIM}} = \frac{2^{M-2}+2\alpha+1}{\alpha M} \mathrm{BW_{OOK}} \tag{16}$$

The bandwidth required for PPIM, DPIM, DH-PIM and MDH-PIM modulations normalized to the OOK modulation bandwidth is shown in Fig. 8 in M. As shown in Fig. 8, the bandwidth required for the MDH-PIM1 modulation is roughly equal to that required for the DH-PIM2 modulation but is much better than the bandwidth required for PPIM, DPIM, and DH-PIM1 modulations; particularly for $M > 5$. For $\alpha > 1$ and $M > 5$, MDH-PIM requires less bandwidth than other modulations. The reason is that an increase in α leads to an increase in the length of the output pulse in the MDH-PIM modulation. Also, following an increase in M, the length of the output frame in the modulator becomes much shorter than the PPM, DPIM, and DH-PIM modulators, thereby widening the length of the output slots and reducing the bandwidth.

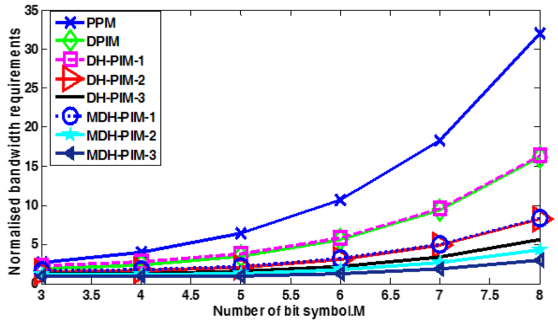

Fig. 8. Normalized bandwidth for PPM and DPIM, DH-PIM and MDH-PIM modulations as compared with the bandwidth of the OOK modulation.

B. Transfer Rate (Transfer Capacity)

The transfer rate or transfer capacity means the number of bits that the modulator modulates and prepares to send at a specified time. It is obvious that the OOK and PPM modulations have equal transfer rates. However, the transfer capacity in the DPIM and DH-PIM modulations is far greater than that of the PPM modulation [18].

To calculate the transfer rate, we select a packet with N_{pkt} bits. The transfer rate of each packet or the transfer capacity is obtained from the following equation [13]:

$$R_{\mathrm{pkt}} = \frac{R_s}{L_{\mathrm{pkt}}} \tag{17}$$

where $R_s = 1/T_s = \mathrm{BW_{req}}$ represents the transfer rate of each slot or the required bandwidth, and L_{pkt} represents the average length of each packet in terms of slot, which is obtained using the following equation:

$$L_{\mathrm{pkt}} = \frac{N_{\mathrm{pkt}} L_{\mathrm{avg}}}{M} \tag{18}$$

So if we calculate the transfer rate for each modulation, we have

$$R_{\text{pkt-PPM}} = \frac{M \times \text{BW}_{\text{req-PPM}}}{N_{\text{pkt}} 2^M} \tag{19}$$

$$R_{\text{pkt-DPIM}} = \frac{2M \times \text{BW}_{\text{req-DPIM}}}{N_{\text{pkt}} (2^M + 2g + 1)} \tag{20}$$

$$R_{\text{pkt-DH-PIM}} = \frac{\alpha M \times \text{BW}_{\text{req-DH-PIM}}}{N_{\text{pkt}} (2^{M-1} + 2\alpha + 1)} \tag{21}$$

$$R_{\text{pkt-MDH-PIM}} = \frac{\alpha M \times \text{BW}_{\text{req-MDH-PIM}}}{N_{\text{pkt}} (2^{M-2} + 2\alpha + 1)} \tag{22}$$

Fig. 9 shows the transfer rate of packets for the fixed bandwidth of 1MHZ and N_{pkt}=1 kbyte for PPM, DPIM, DH-PIM, MDH-PIM modulations, normalized to the transfer rate or the PPM modulation packet in terms of M.

As shown in Fig. 9, for M> 6, the packet transfer rate is equal in DPIM and DH-PIM$_1$ modulations and is almost twice as much as the packet transfer rate in the PPM modulation. However, the packet transfer rate of DH-PIM$_2$ and MDH-PIM$_1$ is four times as much as the packet transfer rate of the PPM modulation. The packet transfer rate of the DH-PIM$_3$ modulation is six times as much as the packet transfer rate of the PPM modulation, the packet transfer rate of the MDH-PIM$_2$ modulation is eight times as much as the packet transfer rate of the PPM modulation, and the packet transfer rate of the MDH-PIM$_3$ modulation is twelve times as much as the packet transfer rate of the PPM modulation. Therefore, as the results indicate, the MDH-PIM modulation has greater transfer capacity than other modulations.

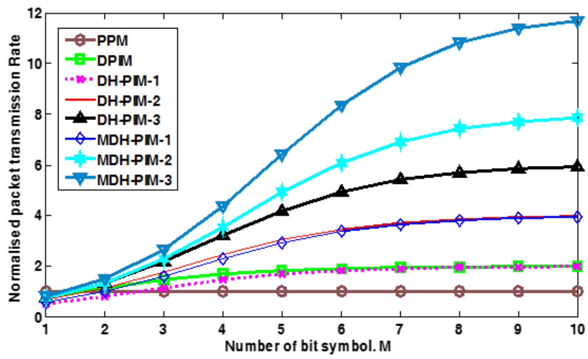

Fig. 9. The transfer rate of the normalized packet for PPM, PPIM, DPIM, DH-PIM$_1$, DH-PIM$_2$, DH-PIM$_3$, MDH-PIM$_1$, MDH-PIM$_2$, and MDH–PIM$_3$ relative to the transfer rate of the PPM modulation packet in terms of M.

C. Average Transmission Power

The average transmission power for each modulated symbol is obtained from the following equation [11]:

$$P(t) = \frac{1}{L_{\text{avg}} T_s} \int_0^{T_s} |x(t)|^2 \, dt \tag{23}$$

Obviously, the modulation power of the OOK modulation is higher than that of other modulations as we may have more than one pulse in each modulated symbol.

Due to constancy of the length of the modulated symbols and their duty cycle in the PPM modulation, all the symbols have an equal average transmission power. However, unlike the PPM modulation, DPIM, DH-PIM and MDH-PIM modulations have different average transmission power rates because the length of the modulated symbols varies. Therefore, due to the fact that the duty cycle of the symbols modulated by DPIM, DH-PIM and MDH-PIM modulations is greater than the duty cycle of the symbols modulated by the PPM modulation, the average transmission power of DPIM, DH-PIM and MDH-PIM modulations is more than that of the PPM modulation.

Also, the duration of the output pulse of the modulator in the DH-PIM and MDH-PIM modulations is higher than that of the PPM modulation depending on the header of each frame, so the average transmission power of the DH-PIM and MDH-PIM modulations is greater than the average transmission power of the DPIM modulation [11]. If we normalize the average transmission power of the PPM, DPIM, DH-PIM and MDH-PIM modulations relative to the average transmission power of the OOK modulation and plot them in M, we will have Fig. 10.

As shown in Fig. 10, the average transmission power of the MDH-PIM modulation is higher than that of other modulations. For example, for M=4, the average transmission power of the MDH-PIM modulation is approximately 1 dB greater than the DH-PIM modulation, 5 dB greater than the DPIM modulation, and 7 dB greater than the PPM modulation.

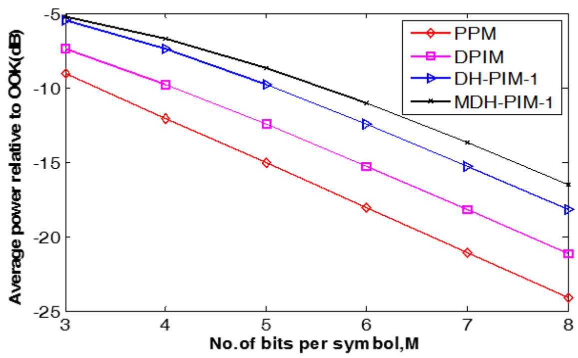

Fig. 10. Average transmission power of PPM, DPIM, DH-PIM, and MDH-PIM modulations relative to the average transmission power of the OOK modulation in terms of M.

D. Error Performance

Errors occur due to various factors including optical noises of the environment, interference of symbols, multi-path propagation, etc. and causes one or more zero bits to be converted to one bits 1 or vice versa.

Fig. 11 shows a wireless optical telecommunications system based on the threshold detector [19].

The modulator block contains one of the digital modulators. The $P(t)$ filter is a rectangular pulse with a length of a slot (T_s). The output of the filter is scaled by the maximum detected signal. The Z values for various modulations are as follows:

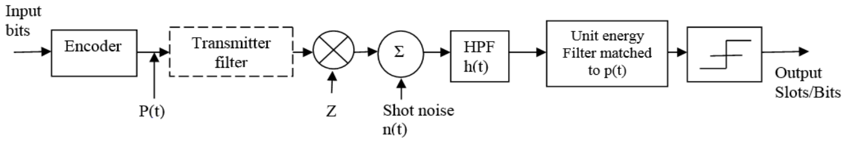

Fig. 11. A wireless optical telecommunications system based on the threshold detector.

$$Z_{\mathrm{OOK}} = R \times P_{\mathrm{avg}} \tag{24}$$

$$Z_{\mathrm{L\text{-}MOD}} = L_{\mathrm{avg\text{-}MOD}} \times R \times P_{\mathrm{avg}} \tag{25}$$

where R represents the photo detector responsivity and P_{avg} represents the mean power of the received optical signal. The filter output ($y(t)$) is sampled with $1/T_s$ frequency , and if its value (y_i) exceeds the threshold level, it is considered one, and if its value is below the threshold level, then it is considered zero.

To calculate the error, we consider the following hypotheses [19], [21]:

1) The communication channel should not be distorted.
2) The transmitter and receiver do not apply any restrictions on bandwidth.
3) The optical signal does not interfere with other light sources.
4) Error in each slot invalidates the entire packet.

Now we calculate the error considering the above conditions.

Like the DPIM and DH-PIM modulations, the length of the modulated symbols is variable in the MDH-PIM modulation and more importantly, each symbol starts with the "1" bit, so any error will create an error not only in that symbol but also in its previous symbol. The energy of each pulse that appears in the filter output is equal to [22]

$$E_{\mathrm{P\text{-}MDH\text{-}PIM}} = \frac{16R^2 P_{\mathrm{avg}}^2 ML_{\mathrm{avg}}}{9\alpha^2 R_b} \tag{26}$$

Suppose that the level of the threshold is considering between zero and one. In this case, the probability of a slot error is equal to

$$P_{\mathrm{e\text{-}slot}} = Q\left(\sqrt{\frac{4ML_{\mathrm{avg}}}{9\alpha^2}\frac{2R^2P_{\mathrm{avg}}^2}{N_0}}\right) \tag{27}$$

where N_0 represents the noise power and $Q(x)$ represents the complementary function of the error [19]:

$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-z^2/2}dz \tag{28}$$

The error probability, PER, of a packet of N-slot length is equal to

$$\mathrm{PER} = 1-(1-P_{\mathrm{e\text{-}slot}})^N \approx NP_{\mathrm{e\text{-}slot}} \tag{29}$$

$$\Rightarrow \mathrm{PER}_{\mathrm{MDH\text{-}PIM}} = NQ\left(\sqrt{\frac{4ML_{\mathrm{avg}}}{9\alpha^2}\frac{2R^2P_{\mathrm{avg}}^2}{N_0}}\right) \tag{30}$$

Since the signal to the electrical noise in the OOK modulation is equal to [20]

$$\mathrm{SNR}_{\mathrm{OOK}} = 2R^2P_{\mathrm{avg}}^2 / N_0 \tag{31}$$

As a result, we have

$$\Rightarrow \mathrm{PER}_{\mathrm{MDH\text{-}PIM}} = NQ\left(\sqrt{\frac{4ML_{\mathrm{avg}}}{9\alpha^2}\mathrm{SNR}_{\mathrm{OOK}}}\right) \tag{32}$$

If we obtain the packet error probability for other modulations in this way, we have

$$\begin{aligned}\mathrm{PER}_{\mathrm{OOK}} &\approx NQ\left(RP_{\mathrm{avg}}\sqrt{2/N_o}\right)\\ &= NQ\left(\sqrt{\mathrm{SNR}_{\mathrm{OOK}}}\right)\end{aligned} \tag{33}$$

$$\begin{aligned}\mathrm{PER}_{\mathrm{L\text{-}PPM}} &\approx NQ\left(RP_{\mathrm{avg}}\sqrt{\frac{LM}{2N_o}}\right)\\ &= NQ\left(\sqrt{\frac{LM}{4}\mathrm{SNR}_{\mathrm{OOK}}}\right)\end{aligned} \tag{34}$$

$$\mathrm{PER}_{\mathrm{DPIM}} = NQ\left(\sqrt{\frac{L_{\mathrm{avg}}M}{4}\mathrm{SNR}_{\mathrm{OOK}}}\right) \tag{35}$$

$$\mathrm{PER}_{\mathrm{DH\text{-}PIM}} = NQ\left(\sqrt{\frac{4ML_{\mathrm{avg}}}{9\alpha^2}\mathrm{SNR}_{\mathrm{OOK}}}\right) \tag{36}$$

Fig. 12 shows the slot error rates for OOK, PPM, DPIM, DH-PIM and MDH-PIM modulations in terms of signal to noise OOK for $M = 4$.

As you can see, the DPIM error is nearly equal to the error of the DH–PIM$_1$, and the error of MDH–PIM$_1$ is greater than the error rates of DH–PIM$_1$, DPIM, and PPM, but less than the error rates of DH–PIM$_2$ and DH–PIM$_3$. The greater the α value, the greater the error of the MDH–PIM$_\alpha$ and the closer to the OOK error. Therefore, we can select a small value for α in order to reduce the error of the MDH-PIM modulation.

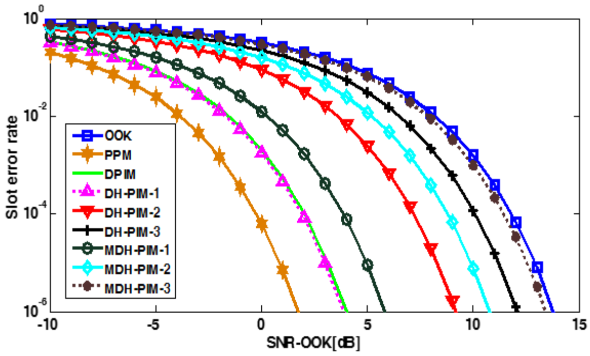

Fig. 12. Slot error rates for OOK, PPM, DPIM, DH-PIM$_1$, DH-PIM$_2$, DH-PIM$_3$, MDH-PIM$_1$, MDH-PIM$_2$, and MDH-PIM$_3$ in terms of signal to noise OOK for $M = 4$.

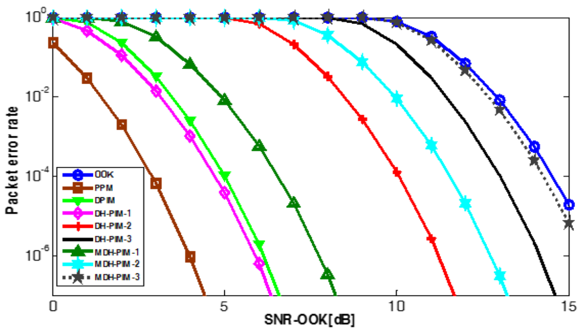

Fig. 13. Slot error rates for OOK, PPM, DPIM, DH-PIM$_1$, DH-PIM$_2$, DH-PIM$_3$, MDH-PIM$_1$, MDH-PIM$_2$, and MDH-PIM$_3$ modulations in terms of signal to noise OOK for M = 4 and the packet length of 1024.

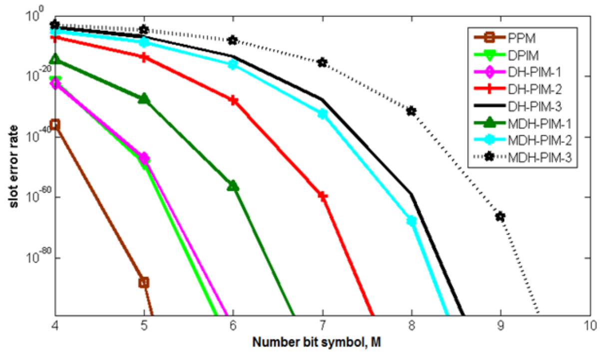

Fig. 14. Slot error rates for PPM, DPIM, DH-PIM$_1$, DH-PIM$_2$, DH-PIM$_3$, MDH-PIM$_1$, MDH-PIM$_2$, and MDH-PIM$_3$ modulations in terms of M.

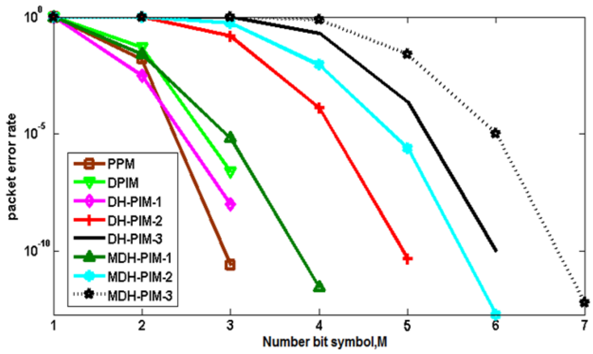

Fig. 15. Packet error rates for PPM, DPIM, DH-PIM$_1$, DH-PIM$_2$, DH-PIM$_3$, MDH-PIM$_1$, MDH-PIM$_2$, and MDH-PIM$_3$ modulations in terms of M.

Fig. 13 shows the packet error rates for OOK, PPM, DPIM, DH-PIM and MDH-PIM modulations in terms of signal to noise OOK for M = 4 and the packet length of 1024, which has the same result as the slot error rates.

Fig. 14 and Fig. 15 show the slot error rates and packet error rates for PPM, DPIM, DH-PIM and MDH-PIM modulations in M respectively. As shown in Figures, the error decreases following an increase in the M value. Therefore, we can select a higher value of M in order to decrease the error of the MDH-PIM modulation.

E. Required Optical Power

One of the important parameters used to evaluate the performance of optical systems is the optical power required in terms of the bandwidth. This means that an ideal optical system is one that needs the lowest power and the lowest bandwidth [22]. In this section we obtain the optical power required for the above modulations using the packet error rate explained in the previous section. As we saw in the previous section, the packet error rate for the OOK modulation is equal to

$$\mathrm{PER}_{\mathrm{OOK}} \approx NQ\left(RP_{\mathrm{avg}}\sqrt{\frac{2}{N_o}}\right) \tag{37}$$

If we obtain the power required for the OOK modulation using the above equation, we have

$$P_{\text{req-ook}} = \frac{1}{R}\sqrt{0.5N_0}\,Q^{-1}\left(\frac{\mathrm{PER}_{\mathrm{OOK}}}{N}\right) \tag{38}$$

If we get the power required for other modulations using this equation, we have

$$P_{\text{req-PPM}} = \frac{2}{\sqrt{LM}}P_{\text{req-ook}} \tag{39}$$

$$P_{\text{req-DPIM}} = \frac{2}{\sqrt{L_{\mathrm{avg}}M}}P_{\text{req-ook}} = \sqrt{\frac{8}{(L+3)M}}P_{\text{req-OOK}} \tag{40}$$

$$P_{\text{req-DH-PIM}} = \sqrt{\frac{9\alpha^2}{4ML_{\mathrm{avg}}}}P_{\text{req-ook}} \tag{41}$$

$$P_{\text{req-MDH-PIM}} = \sqrt{\frac{9\alpha^2}{4ML_{\mathrm{avg}}}}P_{\text{req-ook}} \tag{42}$$

Fig. 16 shows the power required for OOK, PPM, DPIM, DH-PIM and MDH-PIM modulations normalized to the power required for the OOK modulation in M. As you can see in Fig. 16, the power required for the DPIM modulation is much less than the power required for the OOK modulation but is slightly higher than that required for the PPM modulation. For example, for M = 4, the DPIM modulation requires about 5.1 dB less power than the OOK, but needs 2.4 dB more power than the PPM modulation. For M> 4, the power required for MDH-PIM$_1$ modulation is less than that required for DH-PIM$_2$, DH-PIM$_3$, MDH-PIM$_2$ and MDH-PIM$_3$, but a little more than the PPM, DPIM, and DH-PIM$_1$. The greater the α value, the more power is required by the MDH-PIM$_\alpha$ and the closer it gets to the power required for the OOK modulation. Therefore, we can reduce the power required for the MDH-PIM modulation by reducing the α value.

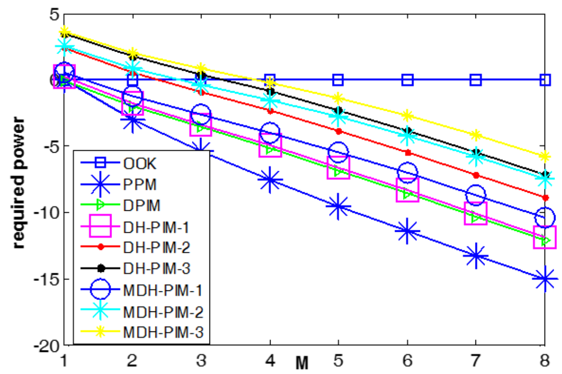

Fig. 16. The power required for OOK, PPM, DPIM, DH-PIM and MDH-PIM modulations normalized to the power required for the OOK modulation in M.

TABLE II. COMPARISON OF DIGITAL MODULATION PARAMETERS

Modulation parameter	Modulation scheme			
	PPM	DPIM	DH-PIM	MDH-PIM
Required bandwidth	High	Average	Low	Very low (advantage)
Transmission capacity	Low	Average	High	Very high (advantage)
Transmission power	Low	Average	High	Very high (advantage)
Error	Low	Average	High	Very high (disadvantage)
Required power	Low	Average	High	Very high (disadvantage)

Table II summarizes the parameters described above. As shown in this table, the MDH-PIM modulation is much better than the other modulations in terms of the bandwidth required to perform the modulation, the transmission capacity and transmission power, but worse than them in terms of the error rate and the power required to perform modulation. However, we can reduce the error rate in this modulation by decreasing the α value or increasing the M value, in which case the power required to perform modulation will also decrease. Therefore, we can manage the error rate and power required to perform modulation in the MDH-PIM modulation by choosing appropriate values of α and M.

V. CONCLUSIONS

Digital modulations act like a digital encoder, and, in addition to providing information to be sent by optical links, they encrypt data and are useful for insecure channels and military applications. Among the digital modulations, the MDH-PIM modulation is an isochronous scheme and uses this capability to synchronize the modulated frames.

The frames in modulated in the MDH-PIM modulation are shorter in length than those modulated in the DPIM and DH-PIM modulations, and this improved the transmission capacity, required bandwidth and transmission power of the MDH-PIM modulation. The bandwidth of the MDH-PIM_1 modulation is similar to that of the DH-PIM_2 modulation, but is better than the bandwidths of PPM, DPIM, and DH-PIM_1 modulations (especially for M>5). Regardless of the M value, the MDH-PIM_2 modulation needs less bandwidth than other modulations, but requires more power to perform modulation. Therefore, we use the MDL-PIM_2 modulation where there is a bandwidth limit, but no problem with power. For large values of M, the transmission capacity of the DH-PIM_1 and DPIM modulations is twice as much as that of the PPM modulation, while the MDH-PIM_2 modulation has a transfer capacity roughly eight times as much as the PPM modulation. The results of this paper showed that the slot error rate and packet error rate of the MDH-PIM modulation decreases following an increase in the M value. Furthermore, a decrease in the value of α will lead to a decrease in the slot error rate and packet error rate of the MDH-PIM modulation.

REFERENCES

[1] A. Asghari-varzaneh and M. H. Ghezel-ayagh, "Imple mentation of DPIM MODEM with FPGA and comparison of its functionality with PPM MODEM," *The Scientific Journal of Advanced Defense Science & Technology*, vol. 3, no. 1, pp. 39-47, 2012.

[2] G. Kaur, H. Singh, and A. S. Sappal, "Free space optical using different modulation techniques," *Int. Journal of Engineering Trends and Technology (IJETT)*, vol. 43, no. 2, pp. 109-115, Jan. 2017.

[3] K. Peppas, A. Boucouvalas, Z. Ghassemloy, M. Khalighi, and K. Yiannopoulos, "Semiconductor optical amplifiers for underwater optical wireless communications," *IET Optoelectronics*, vol. 11, no. 1, pp. 15-19, 2017.

[4] Z. Ghassemlooy, A. R. Hayes, and B. Wilson, "Reducing the effects of intersymbol interference in diffuse DPIM optical wireless systems," *IEE Proc.: Optoelectronics*, vol. 150, no. 5, pp. 445-452, 2013.

[5] T. Ismail, E. Leitgeb, Z. Ghassemlooy, and M. Al-Nahhal, "Performance improvement of FSO system using multi-pulse PPM and SIMO under atmospheric turbulence conditions and with pointing errors," *IET Networks*, vol. 7, no. 4, pp. 165-172, 2018.

[6] Z. Ghassemlooy, S. Zvanovec, M. A. Khalighi, W. O. Popoola, and J. Perez, "Optical wireless communication systems," *Optik*, vol. 151, pp. 1-6, Dec. 2017.

[7] R. M. Hagem, "FPGA based implementation of pulse position modulation for underwater optical wireless communication," *Int. Journal of Engineering and Innovative Technology (IJEIT)*, vol. 6, no. 5, pp. 47-50, Nov. 2016.

[8] M. R. Bhatnagar, Z. Ghassemlooy, S. Zvanovec, M. A. Khalighi, and M. M. Abadi, "Quantized feedback based differential signaling for free-space optical communication system," *IEEE Trans. on Communications*, vol. 64, no. 12, pp. 5176-5188, 2016.

[9] M. Ijaz, R. Kharel, E. Sunday, Z. Ghassemlooy, H. Le-Minh, and X. Tang, "Performance evaluation of free space optical communication under the weak turbulence regime," in *Proc. 10th Int. Symp. on Communication Systems, Networks and Digital Signal Processing*, Prague, Czech Republic, 2016, pp. 1-5.

[10] X. Mi and Y. Dong, "Polarized digital pulse interval modulation for underwater wireless optical communications," in *Proc. OCEANS 2016*, Shanghai, 2016, pp. 1-4.

[11] A. M. Ghafour and E. Zahedi, "Comparison of selected digital modulation schemes (OOK, PPM and DPIM) for wireless optical communications," presented at the 4th Student Conf. on Research and Development, Malaysia, 2006.

[12] Z. Tieying, X. Chuanjun, K. Ting, and M. Jie, "A novel modified digital pulse interval modulation for optical wireless communications," presented at the 4th Int. Conf. on Wireless Communications, China, 2005.

[13] A. R. Hayes, Z. Ghassemlooy, and N. L Seed, "Optical wireless communication using digital pulse interval modulation," *Proc. of SPIE*, vol. 3532, 1999.

[14] N. M. Aldibbiat, Z. Ghassemlooy, and R. Mclaughlin, "Performance of dual header-pulse interval modulation (DH-PIM) for optical wireless communication systems," *Optical Wireless Communications III*, vol. 4214, pp. 1–9, Feb. 2001.

[15] N. M. Aldibbiat, Z. Ghassemlooy, and R. McLaughlin, "Indoor optical wireless systems employing dual header pulse interval modulation (DH-PIM)," *Int. J. Communications. Syst.*, vol. 18, no. 3, pp. 285-305, 2005.

[16] M. Doniec, X. Anqi, and D. Rus, "Robust real-time underwater digital video streaming using optical communication," in *Proc. IEEE Int. Conf. on Robotics and Automation*, 2013, pp. 5117-5124.

[17] C. Singh, J. John, and K. K. Tripathi, "A review on indoor optical wireless systems," *Optical and Quantum Electronics*, vol. 19, no.1, pp. 3-17, 2015.

[18] M. Audeh, J. Kahn, and J. Barry, "Decision-feedback equalization of pulse-position modulation on measured nondirected indoor infrared channels," *IEEE Trans. On Commun*. vol. 47, no. 4, pp. 500-503, 1999.

[19] Z. Ghassemlooy and A. R. Hayes, "Digital pulse interval modulation for IR communication systems-a review," *Int. Journal of Communication Systems*, vol. 13, no. 7, pp. 519-536, 2000.

[20] N. Aldibbiat, Z. Ghassemlooy, and R. Saatchi, "Pulse Interval Modulation – dual header (PIM-DH)," *IEEE Communications Magazine*, vol. 36, no. 14, pp. 45-50, 2007.

[21] S. Rajbhandari, Z. Ghassemlooy, P. A. Haigh, T. Kanesan, and X. Tang, "Experimental error performance of modulation schemes under a controlled laboratory turbulence FSO channel," *Journal of Lightwave Technology*, vol. 33, no. 1, pp. 244-250, 2015.

[22] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling with MATLAB*, New York: CRC Press, 2017.

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