# Investigation of Suitable Modulation Techniques for Underwater Wireless Optical Communication

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***Abstract*— For an underwater wireless optical communication system, we consider the use of different intensity modulation techniques, and compare their performance by taking realistic system parameters into account. In particular, we contrast the performances of on-off keying, pulse position modulation, pulse width modulation, and digital pulse interval modulation, when a PIN or an avalanche photodiode is used at the receiver. We discuss the suitability of these modulation techniques to the underwater optical channel by considering the implementation issues.**

## I. Introduction

Thanks to its advantages of cost-effectiveness and power-efficiency, optical communication has received a great attention since a few years and has been considered as an attractive transmission technique for underwater wireless sensor networks (UWSN). Optical propagation in water is subject to high absorption and scattering leading to strong light intensity attenuation. Fortunately, in most practical situations, high data-rate communication over medium transmission ranges is possible without suffering from any inter-symbol-interference (ISI) [1], [2]. In the UWSN context, one critical issue is the nodes' power consumption that should be minimized through the choice of adequate equipments and data transmission techniques. Energy efficiency, in turn, depends on the optical modulation scheme as well as on the receiver detection and signal processing parts among other factors.

We would like in this work to compare the performance of different modulation techniques from the point of view of energy efficiency while taking into account other important factor such as bandwidth (BW) efficiency and the receiver implementation complexity. We focus on intensity modulation and direct detection (IM/DD) techniques due to the transceiver cost and implementation complexity concerns. More specifically, we study the four modulation techniques of ON-OFF keying (OOK), pulse position modulation (PPM), pulse width modulation (PWM), and digital pulse interval modulation (DPIM). We consider realistic system parameters and the two cases of using a PIN photo-detector (PD) and an avalanche photodiode (APD) at the receiver, and compare these modulation schemes from the point of view of maximum achievable transmission range conditioned to a target bit-error-rate (BER) performance.

In Section II, we briefly present the considered modulations and the main considerations related to them. Then, some numerical results are presented in Section III to compare their performance. Lastly, concluding remarks are provided in Section IV.

## II. Brief description of modulation schemes

We provide in this section a brief introduction to the modulation techniques we consider, as well as their pros and cons. An example of bit-symbol mapping is illustrated in Fig. 1 to help the reader follow the discussions. To do a fair comparison between the different schemes, we fix the transmission bit rate to $R_b$ and the average transmit optical power to $P_{\text{av}}$ for all modulations.

### A. OOK

The classical OOK is widely used in fiber and free-space optical communication due to its implementation simplicity [3]. We consider the non-return-to-zero OOK modulation and denote the symbol duration by $T_{\text{OOK}}$. Then, the required BW $B$ is equal to $R_b$ and the transmit optical power per ON slot is $P_{\text{ON}} = 2\,P_{\text{av}}$.

### B. PPM

For a direct-detection optical link, under peak and average power constraints, a slotted binary modulation like PPM can nearly achieve the channel capacity [3]. When performing hard signal detection at the receiver, PPM has the advantage that, in contrary to OOK, it does not require dynamic thresholding for optimal detection. Consider the classical $L$-ary PPM where a symbol corresponds to $M = \log_2 L$ bits. Also, let $T_{\text{PPM}}$ and $T_s$ denote the symbol and slot durations, respectively, where $T_s = T_{\text{PPM}}/L$. We have $T_{\text{PPM}} = T_{\text{OOK}}(\log_2 L)$ and $P_{\text{ON}} = L\,P_{\text{av}}$.

The important advantage of PPM over OOK is that it is more average-energy efficient. However, this comes at the expense of lower BW efficiency [4]; The required BW for $L$-PPM is $B = LR_b/(\log_2 L)$ which increases with $L$. Although a large BW is usually available in optical communication, a larger $L$ results in a higher peak-to-average power ratio (PAPR), necessitates a higher switching speed for the electronic circuits, and also makes the receiver slot synchronization more difficult.

### C. PWM

For $L$-ary PWM with $M = \log_2 L$, we use the same symbol duration $T_{\text{PWM}}$ as $T_{\text{PPM}}$, but the duration of ON slots is varied between $T_s$ and $L\,T_s$. Hence, $P_{\text{ON}} = 2P_{\text{av}}/(L{+}1)$. In contrast to PPM, PWM requires less peak power $P_{\text{ON}}$, has a better spectral efficiency, and is more resistant to ISI, especially for larger $L$ [5]. Nevertheless, these advantages are counterbalanced by higher power requirements of PWM that increases with $L$. For receiver noise calculations, we consider the average BW for PWM that is given by $B = 2LR_b/((1+L)\log_2 L)$.

### D. DPIM

By DPIM, for each symbol, an ON slot of duration $T'_s$ is sent followed by a number of OFF slots depending on the $M$ input bits [6], [7]. An additional guard slot (GS) is also added, in general, to avoid sending consecutive ONpulses. Due to this reason, it is sometimes called 1GS-DPIM. We have $P_{\text{ON}} = (L+3)P_{\text{av}}/2$. Also, the average symbol duration for DPIM is $\overline{T_{\text{DPIM}}} = (L+3)T'_s/2$ and the required average BW is $B = (L+3)R_b/(2\log_2 L)$ [7].

PPM and PWM are usually called *isochronous* and *synchronous* modulations because they map the input bits on a symbol of fixed duration. Both schemes require slot- and symbol-level synchronization. In contrast, DPIM is an *anisochronous* and *asynchronous* time modulation scheme with variable symbol length, and does not require symbol synchronization [7]. In addition, it is more BW efficient than PPM and PWM, because we should not wait the end of a fixed symbol period before sending the next symbol. The main potential problem with DPIM is the error propagation in signal demodulation at the receiver.

### E. Other related IM/DD modulations

Various extensions to PPM have been proposed in the literature so far. By multi-pulse PPM (MPPM), several ON slots are transmitted during a symbol duration that results in reduced PAPR and a higher BW efficiency, at the expense of increased demodulation complexity [8]. When the multiple pulses are conditioned to occupy adjacent slots, MPPM is called overlapping PPM (OPPM) [9]. By differential PPM (DPPM), in a PPM symbol, the OFF slots following an ON slot are removed. This releases the symbol synchronization requirement and improves the BW efficiency [10]. By digital pulse interval and width modulation (DPIWM), the binary sequence is encoded in the width of the pulses of alternating amplitude [11]. PPMPWM, proposed in [5], is a combination of PPM and PWM with power and BW efficiencies in mid-way between PPM and PWM [12]. The main disadvantages of these PPM derivations are their reduced energy efficiency, their relatively high demodulation complexity, and the risk of error propagation in detecting a received frame of symbols.

Note that, except OOK, the schemes that we considered above are time modulation techniques. Pulse amplitude modulation (PAM), with OOK as its simplest scheme, may also be a choice. However, by $L$-ary PAM, the laser intensity is modulated on $L$ levels [3]. This requires a laser with a variable emission intensity which is costly.

## III. Numerical results

We present here simulation results based on the Monte Carlo approach presented in [2] to compare the performances of the four modulation techniques retained in Section II. Our performance criterion is the maximum attainable link distance for an average transmit optical power of $P_{\text{av}} = 0.1\,\text{W}$ and a transmission bit-rate of $R_b = 100\,\text{Mbps}$, conditioned to a target BER of $10^{-6}$.

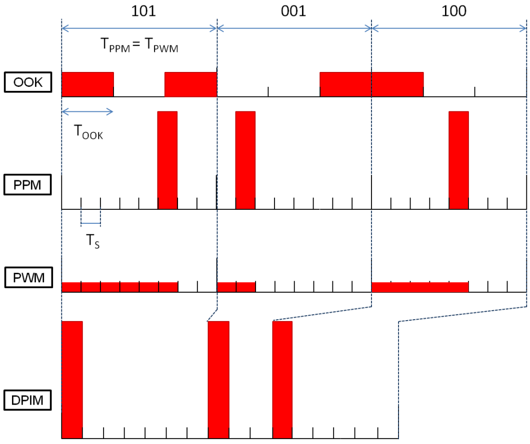


Fig. 1. Example of bit-symbol mapping for OOK, PPM, PWM, and DPIM with 1 GS. $L = 8$.

We consider uncoded modulation over the frames of length 1024 bits using a quasi-monochromatic 532 nm LED of initial divergence angle $20°$. This way, we relax exact underwater node positioning requirement. We consider communication in deep waters where sunlight cannot penetrate and we can effectively neglect background radiations. We assume that the communication takes place in clear ocean waters with a typical chlorophyll concentration of $0.31\,\text{mg}\,\text{m}^{-3}$, resulting in an absorption coefficient of $a = 0.069\,\text{m}^{-1}$ and a scattering coefficient of $b = 0.08\,\text{m}^{-1}$, which are the main parameters related to optical wave propagation [2]. On the receiver side, we consider the use of a PIN diode and an APD with quantum efficiencies of $\eta = 0.82$ and $0.78$, respectively, and the cut-off frequency of $f_c = 300\,\text{MHz}$. Given the limited $f_c$, we should limit $L$ to 8 for PPM, PWM, and DPIM modulations. The PD is placed at the focal plane of a large collimating lens of diameter $D = 20\,\text{cm}$ and focal distance $F = 25\,\text{cm}$. Considering a 3.0 mm active area diameter for the PD, the receiver field-of-view (FOV) is $0.69°$, which is taken into account in our simulator.

### A. Case of PIN diode

Figure 2 shows the curves of BER as a function of $Z$ for the different modulations when a PIN PD is used at the receiver. In this case, the receiver dominant noise is the thermal noise whose variance is proportional to $B$ [13]. We notice that, for a target BER of $10^{-6}$, the link distance is limited to 26 m when OOK is used. For $L$-PWM, this distance is about 19.5 m for $L = 2$, and it decreases for larger $L$. $L$-PPM enables larger transmission ranges especially for increased $L$; Z is limited to about 32 m for $L = 8$. Notice that for $L = 2$, we have the same performance as for OOK. $L$-DPIM, on the other hand, is slightly less efficient than $L$-PPM; it outperforms OOK for $L = 4$ and 8.

### B. Case of APD

We consider an APD of maximum gain $G = 50$. For this case, the dominant receiver noise is the APD shot noise which is proportional to $G$ [13]. Here, for

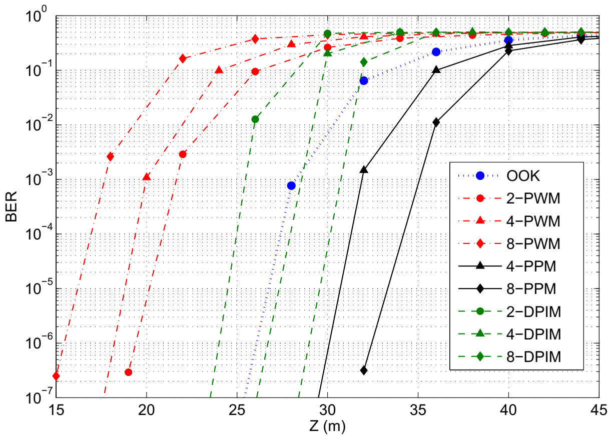


Fig. 2. BER performance for different modulations. $P_{\rm av} = 0.1$ W, $R_b = 100$ Mbps. PIN photodiode with $f_c = 300$ MHz and $\eta = 0.82$. Receiver parameters: $D = 20$ cm $F = 25$ cm, FOV$= 0.69°$.

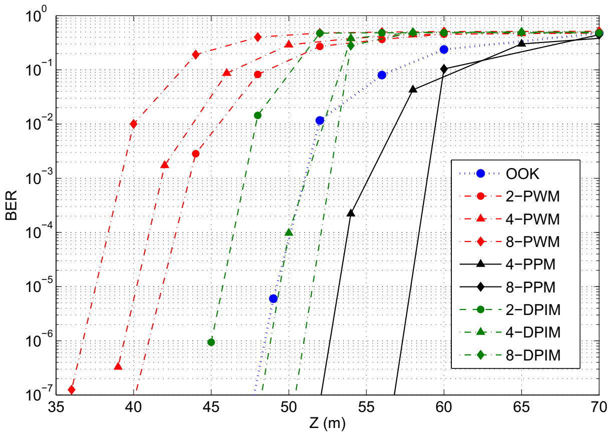


Fig. 3. BER performance for different modulations. $P_{\rm av} = 0.1$ W, $R_b = 100$ Mbps. APD with $f_c = 300$ MHz, $\eta = 0.78$, and $G = 50$. Receiver parameters: $D = 20$ cm $F = 25$ cm, FOV$= 0.69°$.

each link distance $Z$, we use the optimal $G$ that maximizes the receiver signal-to-noise ratio (SNR) [14]. The corresponding results are shown in Fig. 3. As expected, compared with the PIN case, we notice a significant improvement in the system performance, whatever the modulation scheme is. The attainable link distances are increased by about 22 m in average and are summarized in Table I together with those for the PIN case. It should be noticed that the advantage of APD comes at the expense of increased implementation complexity. In particular, we need a relatively high voltage for APD reverse biasing that necessitates the use of special electronic circuits. This also results in an increase in the receiver power consumption.

## IV. Conclusions

In the highly challenging underwater environment, the power resources are limited and their optimization is primordial. We compared different modulation techniques from the point of view of achievable link distance. Although PPM remains the most energy efficient modulation scheme, from the presented results we noticed that DPIM

TABLE I

Maximum link distance for PIN- and APD-based receivers. $P_{\rm AV} = 0.1$ W, $R_b = 100$ Mbps, BER$= 10^{-6}$.

| Modulation scheme | $Z$ with PIN | $Z$ with APD |
|---|---|---|
| OOK, 2-PPM | 26 m | 48 m |
| 4-PPM | 30 m | 53 m |
| 8-PPM | 32 m | 57 m |
| 2-PWM | 19 m | 41 m |
| 4-PWM | 18 m | 39 m |
| 8-PWM | 15 m | 37 m |
| 2-DPIM | 23 m | 45 m |
| 4-DPIM | 27 m | 49 m |
| 8-DPIM | 29 m | 51 m |

can also considered as a more suitable choice than the classical OOK. The better BW efficiency and PAPR of DPIM, as compared to PPM, are obtained at the expense of more computationally complex demodulation, however.


## Acknowledgment

The authors wish to thank Prof. Hassan Akhouayri from Institut Fresnel for the discussions on the implementation aspects concerning the transmitter/receiver optics.


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