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An Efficient Pulse Position Modulation Scheme to Improve the Bit Rate of Photoacoustic Communication

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Abstract*—Wireless communication from air-to-underwater is quite challenging because of the lack of proper physical signal that propagates well in both air and water medium. Photoacoustic energy transfer mechanism is the most promising method for such cross-medium communication, where a high energy pulsed light is focused on the water surface, causing the generation of an acoustic signal inside the water. Since acoustic signals can travel a long distance inside the water, this method enables an airborne unit to reach nodes at increased underwater depth. Yet the achievable bit rate for this process is very low. When a pulsed laser light with a higher repetition rate is focused inside the water, a vapor cloud is generated around the focus point, which blocks subsequent generation of acoustic signal and consequently limits the achievable bit rate. This paper opts to overcome such a limitation by proposing a novel pulse position modulation technique which can avoid such generation of vapor cloud and increases the bit rate significantly.

Keywords: Photoacoustic communication; Underwater networks; Cross-medium communication; Modulation.

I. Introduction

The application of underwater communication can be found in the civil, military, and scientific domains. Environmental monitoring, rescue-and-search, security surveillance, and oceanographic data collection are some examples of these applications. With the advances of technology and prevalence of the notion of internet of everything, ad-hoc and agile networking of terrestrial and underwater nodes have become desirable, especially where almost 70% of the earth surface is covered by water. However, achieving such an objective is quite challenging because there is no physical signal that propagates smoothly in both air and water medium. While radio frequency (RF) is predominantly used in terrestrial communication, RF signals suffer major attenuation in water. Similarly, low frequency acoustic or sonar signals are commonly used for communication in the underwater environments [1][2]; yet, when a low frequency acoustic signal is transmitted from air to underwater, most of the signal energy will be reflected back from the water surface [3].

Visible light communication (VLC) or free space optics could be a viable option for air-to-water communication [4]. Since the transmittance of light at the air-water interface is very high, the achievable bit rate using VLC is high as well [5][6]. However, light attenuates exponentially with the increase of underwater distance. Such attenuation also depends on the purity of the water medium. Hence, VLC is not a good option for reaching nodes at large depths. Microwave is another alternative for air-to-underwater communication [7]; yet the generated signal is still weak for supporting long distance communication. The photoacoustic energy transfer mechanism avoids these shortcomings. When a sufficiently high energy pulsed laser light is focused on the water medium from the air medium, an acoustic signal is generated in the water. Such a phenomenon is usually referred to as the photoacoustic (PA) effect.

Depending on the state of the water medium through this process could be either linear or non-linear photoacoustic. Non-linear photoacoustic can generates a stronger signal than the linear counterpart. This is hybrid method because in the transmitter side a light signal is transmitted while at the receiver side an acoustic signal is received. The photoacoustic effect has been popular in the areas of medical imaging [8][9][10] and instrumentation [11]. However, its use for cross-medium communication is relatively new. In recent years, there has been some notable research work to validate the effectiveness of the photoacoustic for air-to-water communication. In [12], a low-cost passive relay has been placed on the water surface to boost the energy conversion efficiency. However, deploying such a type of relays could be logistically very complicated for many practical applications.

Blackmon et al. [13][14][15] have conducted a rigorous time and frequency domain analysis of the acoustic signal that is generated via photoacoustic mechanism. Such analysis shows that the generated acoustic signal has angle dependency i.e., position of transmitter in the air and the receiver in the water. The acoustic signal is also found to be very broadband in nature. The frequency that contains maximum energy is called the peak frequency. The relation between peak frequency and input laser power has been shown in [16]. However, such a broadband signal is not good for long distance communication, because the higher the frequency of the signal the more it attenuates in water. Therefore, a narrowband signal that contains lower frequencies is desirable for long-distance communication. In our previous work, we have shown that by controlling the position of transmitter and receiver, we can create a narrowband signal [17]. Moreover, in [18], Y. H. Berthelot has shown how to create a narrowband acoustic signal by controlling the laser repetition rate.

Most of the aforementioned research work on photoacoustic communication has focused on signal quality. Little attention has been given to developing a suitable modulation scheme that handles the complexity of the hybrid signals; that is modulating

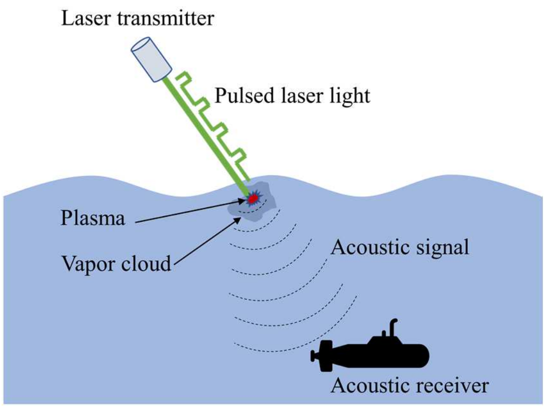

Fig. 1. Photoacoustic mechanism for air-to-underwater communication

a laser beam and demodulating the corresponding acoustic signal. Recently, we have developed a peak detection based OOK modulation (PDOOK) scheme to overcome this challenge [19]; yet the achievable bit rate using such an OOK-based modulation methodology is low. The bit rate limitation is attributed to the vapor cloud that is created by the laser beam underwater. The generation of acoustic signals through the optoacoustic effect will be hindered until the vapor cloud is dispersed. With the increase of laser pulse repetition rate, the intensity of the vapor cloud becomes high and consequently acoustic signals are not generated at a proportional rate. Therefore, the laser pulse repletion rate will be capped and in turn, the achievable bit rate.

This paper opts to overcome the constraints that the vapor cloud imposes on the bit rate by developing a novel modulation technique. Our proposed modulation scheme is based on pulse position modulation (PPM). We have developed a PPM frame where we carefully add an extra time slot which helps to avoid the effect of vapor cloud. Not only the proposed frame can avoid the effect of vapor cloud but also achieve higher bit rates than the traditional OOK modulation. In summary the contributions of this paper are: (1) study the effect of vapor cloud on highest achievable bit rate, (2) develop a new PPM frame to overcome the vapor cloud effect and achieve higher bit rate than the traditional OOK modulation, and (3) optimize the key parameters associated with the designed PPM frame to maximize the bit rate gain, and (4) validate our approach using a prototype system.

The paper is organized as follows. The next section describes system model and some design challenges. Section III provides elaborate description of proposed PPM modulation scheme. The experiments and simulation results are reported in Section IV. Finally, the paper is concluded in Section V.

II. System Model and Design Challenges

This section covers some background about the PA mechanism and highlights the challenges for designing suitable modulation and demodulation schemes.

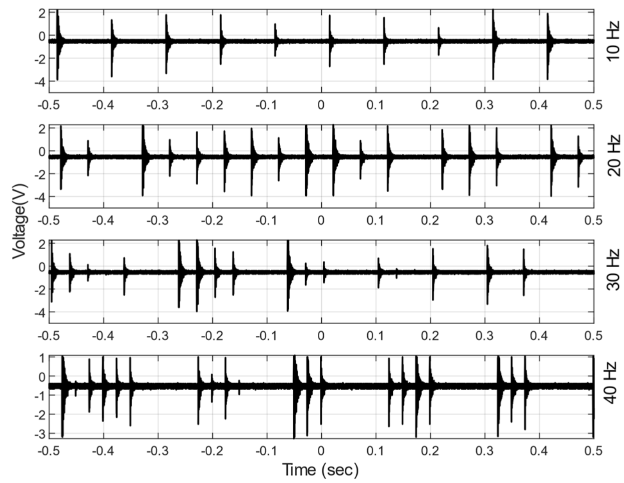

Fig. 2. Effect of vapor cloud on laser pulse repetition rate

A. Photoacoustic Mechanism

Discovery of PA mechanism dates to 1881 and is credited to Alexander Graham Bell. He observed that when reasonably high energy pulsed light is focused inside the water, light energy transforms to acoustic energy. This transformation of energy from light to acoustic is referred to as photoacoustic energy transfer mechanism. Figure 1 explains such a mechanism. This phenomenon further can be divided into two categories. If the state of the water medium doesn't change, it is called linear PA. Here, linear means the strength of the generated acoustic signal is proportional to the applied light energy. In this process, due to the nature of pulsed laser light, temperature fluctuations occurred at the focus point of the light inside the water. Such temperature fluctuation creates a volume fluctuation which eventually creates longitudinal acoustic waves.

On the other hand, when laser light energy exceeds a certain threshold value, the state of the water medium changes, i.e., the water molecule becomes ionized. Such ionization creates plasma, which further generates shockwaves that propagate as acoustic waves in the water. Such a process is referred to as non-linear PA where the strength of the generated acoustic signal is not linearly proportional to the applied light energy. In non-linear PA, the energy conversion rate is higher than the linear counterpart and consequently the generated acoustic signal is stronger. In this paper, we exploit the non-linear PA mechanism for air-to-underwater communication. As mentioned earlier, a minimum threshold energy is required for water molecule ionization, which depends on the laser pulse duration. The necessary threshold energy for nano- and femto-second lasers has been researched in [8], where a laser light irradiance level in the order of 10^{11} W/cm^2 and 10^{13} W/cm^2 are deemed necessary for nano and femto-second laser, respectively.

B. Design Challenges for Modulation Scheme

The use of the PA mechanism to establish a communication link from air to underwater is relatively new. Even though there is some notable work on acoustic signal generation and signal processing, little attention has been given to develop suitable modulation schemes for PA mechanism. There are multiple design challenges associated with PA modulation. First, the PA mechanism involves hybrid signals. At the transmitter side, a light energy is modulated and at the receiver side, an acoustic signal needs to be demodulated. In any conventional communication system, the same kind of signal is modulated and demodulated in the transmitter and receiver module. Hence, special techniques need to be employed for handling such hybrid PA signals. Secondly, the generated acoustic signal in the PA process is very broadband [19], which makes it very difficult to implement any kind of FSK or PSK modulation.

Third and most important factor is the generation of vapor clouds near the laser light focus point on the water. In non-linear PA, the optical breakdown of water creates a temporary vapor cloud near the plasma position [15], and as illustrated in Figure 1. The vapor cloud could block the subsequent acoustic signal generation. To avoid such a scenario, the transmitter needs to wait a minimum duration before sending the next laser pulse. Figure 2 explains such a scenario by showing the received acoustic signal amplitude for different laser pulse repetition rates. The results are obtained through experiments using Nd:YAG laser and a water tank-based prototype in our lab. From this figure, we can observe that with a laser pulse repetition rate of 10 Hz, there is no acoustic pulse missing at the receiver side. However, when the laser pulse repetition rate grows to 20 Hz, a few acoustic pulses are missing. The number of missing acoustic pulses increases rapidly for laser pulse repetition rates of 30 Hz and 40 Hz. In other words, the vapor cloud limits the maximum repetition rate, i.e., maximum achievable bit rate using on-off keying modulation techniques. Recently, we have developed a peak detection based OOK modulation scheme for air-to-underwater non-linear PA communication [19]. Yet, the achievable bit rate through PDOOK is still constrained by the vapor cloud effect. This paper proposes a PPM scheme for non-linear PA communication that mitigates the vapor cloud effect and boosts the bit rate of OOK based modulation.

III. PROPOSED PPM MODULATION SCHEME

We start our discussion with a brief description of PPM and how to design the PPM frame to avoid the effect of vapor clouds. Then we will describe how to design the transmitter and receiver for such a modulation scheme.

A. Frame Design

In PPM, the pulse position represents the value of the input data. The input data is divided into many blocks; each of size *M* bits. The *M*-bit block of input data is mapped to $L = 2^M$ chips, where only one chip is 'on' and the rest of the *L*-1 chips are 'off'. The position of the 'on' chip depends on the equivalent decimal value of the *M*-bit block of input data. The parameter *M* is called the modulation index. Figure 3 gives an example of a PPM encoded data for *M* = 3, where the 6-bits input data is divided into two blocks. The value of *L* will be $2^M = 8$. Hence, every 3 bits input data will be mapped to 8 chips, where the position of the 'on' chip will be based on the decimal value of that 3 bits data. In this example, the decimal

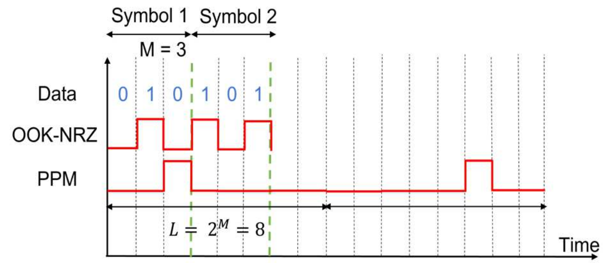

Fig. 3. An example of PPM waveform for *M* = 3, showing also the binary values, and the OOK non-return-to-zero(NRZ) representation.

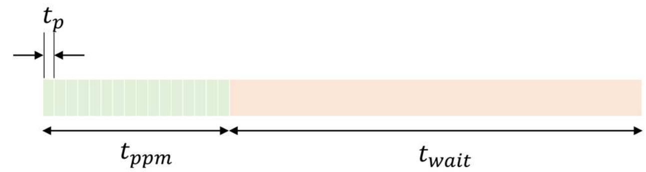

Fig. 4. The proposed PPM frame design

value of the first 3 bits data is 2; therefore, in the first 8 chips of PPM data, there is only one 'on' pulse in the third position. Please note that the first position corresponds to the decimal value of zero.

Figure 4 shows our proposed design of a PPM frame that can avoid the generation of vapor clouds. As discussed in Section II, there is a maximum bit rate or minimum laser pulse repetition rate for which there is no effect of vapor cloud on the generated acoustic signal using OOK modulation. In Figure 4, t_{wait} denotes that minimum duration a transmitter needs to wait before sending next laser pulse. t_{wait} can be defined as follows:

$$t_{wait} = t_{min/OOK} = \frac{1}{r_{max/OOK}} \quad (1)$$

where, $t_{min/OOK}$ is the minimum laser pulse repetition rate which doesn't create vapor cloud. In Figure 4, t_{PPM} is the time required for PPM modulated data for *M* bit input data block. t_{PPM} can be calculated using:

$$t_{PPM} = 2^M \times t_p \quad (2)$$

where, t_p is the time for a PPM chip.
Hence, the total time required to encode *M* bits input data is:

$$t_{total} = t_{PPM} + t_{wait} \quad (3)$$

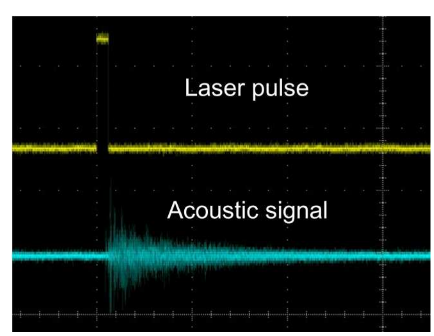

Fig. 5. Pattern of generated acoustic signal for a single laser pulse

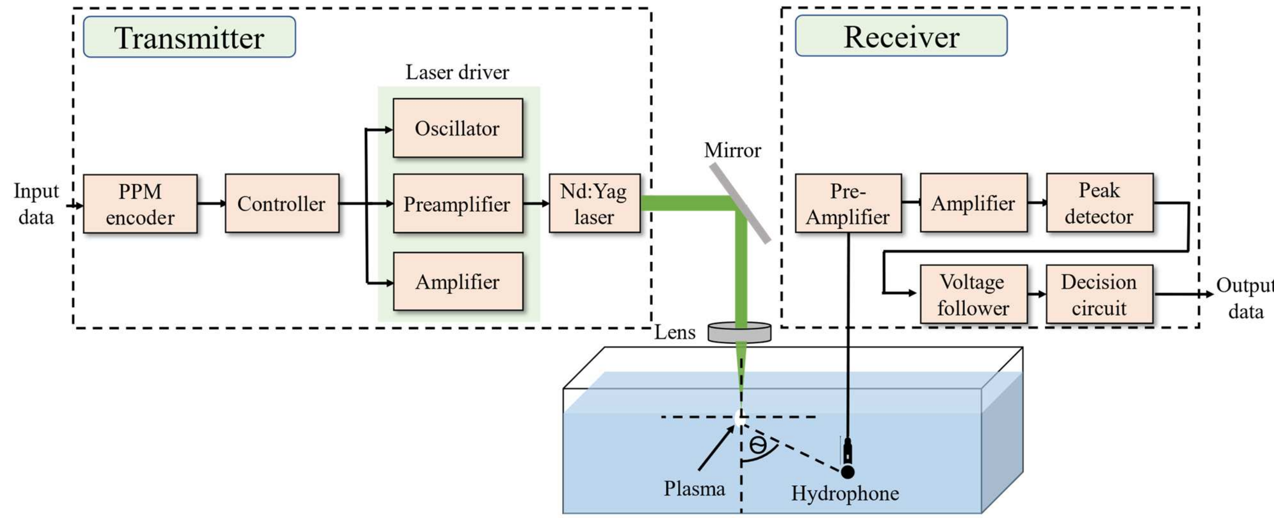

Fig. 6. Block diagram of the transmitter and receiver of pulse position modulation of PA air-to-underwater communication

Transmitting M bits needs t_{total}, consequently the bit rate using our PPM frame would be:

$$r_{PPM} = \frac{M}{t_{total}} \tag{4}$$

Substituting the value of t_{total} from Eq. (1)-(3) into Eq. (4), we get:

$$r_{PPM} = \frac{M}{2^M \times t_p + t_{min/OOK}} \tag{5}$$

Finally, the bit rate gain of PPM over OOK would be:

$$A_{PPM/OOK} = \frac{r_{PPM}}{r_{OOK}} = \frac{M \times t_{min/OOK}}{2^M \times t_p + t_{min/OOK}} \tag{6}$$

In this research work, our goal is to maximize such gain.

B. Transmitter and Receiver Design

To design the transmitter and receiver that suit pulse position modulation of PA communication, it is necessary to understand the nature of the generated acoustic signal for a single laser pulse. Figure 5 captures the relationship between the two signals. From this figure, we can see the generated acoustic signal has multiple peaks and those peaks gradually decrease over time. Due to the damping nature of the acoustic signal, we have used a peak detector at the receiver circuit which can detect the highest peak of such an acoustic signal. The idea is to generate at the transmitter side a PPM frame based on the data and transmit laser pulses according to that PPM frame. The receiver is to detect the acoustic signal and decode the position of "on" chips to successfully determine the transmitted data. In the balance of this subsection, we explain the design of the transmitter and receiver in detail.

Transmitter: The transmitter mainly consists of a laser system, controller, and a PPM encoder. Figure 6 shows the block diagram of a transmitter and receiver of the PA-based air-to-water communication. To create a plasma inside the water a very powerful pulsed laser source is needed. A Q-switch Nd:YAG laser source has such capability. A laser driver is needed to operate the laser source. This laser driver has three main components: pre-amplifier, amplifier, and oscillator. A controller is used to adjust all electric signals of the laser driver. Basically, this controller helps to create a laser pulse at a specific time. A PPM encoder converts the input message data into a PPM modulated data; such modulated data is then fed to the controller which eventually helps to create laser pulse according to the PPM frame we discuss in Section 3.

Receiver: A hydrophone is used as a sensor at the receiver to sense the generated acoustic signal. The generated acoustic signal is very broadband. So, a hydrophone with a broad frequency response is required for this kind of application. An acoustic signal produced by a non-linear PA system typically contains frequency components up to 1 MHz. A hydrophone should sense at least a few hundred KHz frequency components of the acoustic signal to reliably detect the signal at the receiver end, even though a higher frequency component often attenuates with an increase in the distance that the signal travels in the water. A preamplifier and amplifier are used to amplify the received signal.

After the amplification stage, a peak detector is used to detect the peak of the acoustic signal. Figure 7 shows the circuit implementation of the receiver. In this circuit, diode D1,

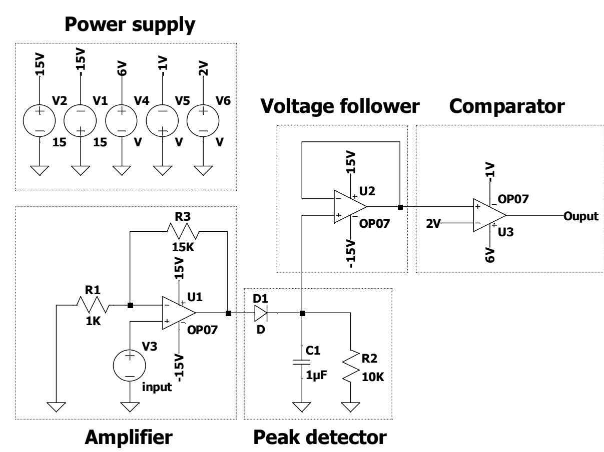

Fig. 7. Circuit diagram of the receiver circuit

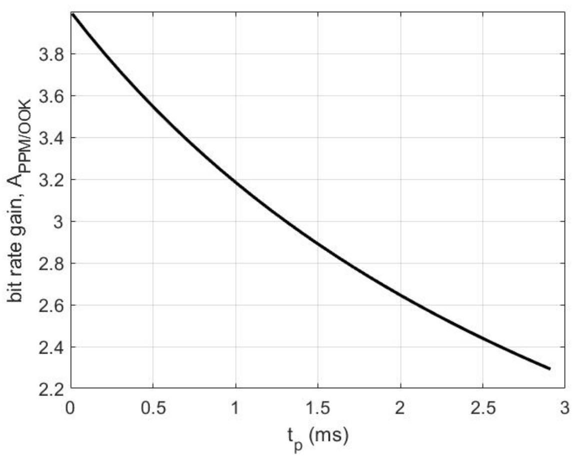

Fig. 8. Effect of PPM chip time, t_p on bit rate gain, $A_{PPM/OOK}$

capacitor, C1, and resistor R2 are used to implement the peak detector. The value of C1 and R2 are chosen in such that the RC time constant is not more than t_p. Finally, a voltage follower and comparator are used to produced two fixed voltage level to successfully distinguish between logic '1' and logic '0'.

IV. Validation Results

Both lab experiment and simulation have been pursued to validate our PPM frame design. Our main goal is to maximize the bit rate with respect to traditional OOK modulation, i.e., maximize the value of $A_{PPM/OOK}$ shown in Eq. (6). Based on such an equation, the value of $A_{PPM/OOK}$ depends on, modulation index, *M*, minimum wait time between two consecutive laser pulses to avoid generation of vapor cloud, t_{wait} and time for a PPM chip, t_p. At first, we will show some simulation results to better understand the effect of *M* and t_p and then we will present our experimental results to show the highest achievable value of $A_{PPM/OOK}$ in our lab setup.

A. Simulation Results

From Eq. (6), it is obvious that $A_{PPM/OOK}$ grows with the decrease of t_p. Figure 8 shows the obtained results. Yet, it is not practically possible to make t_p as small as we want, because with the decrease of t_p, the probability of timing error, t_{err} at the receiver also increases which eventually leads to incorrect decoding of the transmitted data. Here t_{err} means the error of the position of the laser pulse in the PPM frame in the time domain. This timing error can happen for various reasons such as propagation delays of the acoustic wave in the water medium, variation in the response time of the receiver circuit, etc. To successfully decode the received signal t_{err} needs to be less than the t_p. In the next section, we will show the relationship between t_{err} and t_p observed in our experiments, which helps to determine the minimum value of t_p that can be used for successful communication.

The effect of modulation index, *M* on $A_{PPM/OOK}$ for different values of t_p is captured in Figure 9. This figure shows that $A_{PPM/OOK}$ grows as *M* increases up to a certain value,

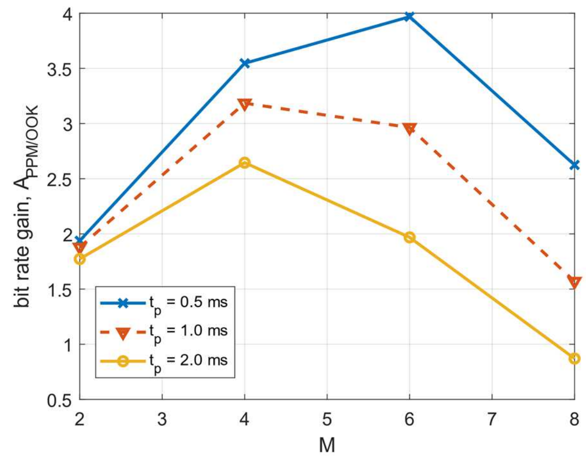

Fig. 9. Effect of modulation index, *M* on bit rate gain, $A_{PPM/OOK}$

where it starts to decline with further growth in *M*. This is mainly because, when the value of *M* is too small, more PPM pulse needs to be sent which means longer t_{wait} time is required to separate the PPM pulses in order to avoid the vapor cloud. On the other hand, if *M* is too large, according to Eq. (2), the PPM frame size becomes large, which reduces the value of $A_{PPM/OOK}$. Once, we confirm the value of t_p, we can choose the best value of *M* from Figure 9.

B. Lab Experiments

As discussed earlier, the non-linear PA effect requires a very powerful pulsed laser source. We have used Geoscience Laser Altimeter System (GLAS) Q-switch Nd:YAG laser for our experiment [20]. The wavelength of the laser source is 1064 µm and the pulse duration is 6 ns. It can produce a laser pulse of 1~50 mj of energy. The maximum repetition rate is 40 Hz. We have used a delay generator as a controller, i.e., to generate all control signals needed to drive the laser [21]. The PPM encoder is implemented on a Xilinx FPGA (Artix-7) [22]. We have developed a Verilog code which can create PPM frames like the one shown in Figure 4 according to the input message data. Mirrors and lenses are required to direct the laser light in the water tank as shown in Figure 6. The lenses also help to create an irradiance in the order of 10^{11} W/cm^2 which is required to generate plasma in non-linear PA. The tests were conducted on a water tank. The tank is made of clear glass and is measured 1.27m (L) × 0.6m (W) × 0.8m (H). The inner sides and bottom of the tank are covered with sound-absorbing material to reduce acoustic signal reflection. We set our hydrophone at a maximum distance of 30 cm from the laser pulse focusing point because of the restricted tank size. Due to the broadband nature of the generated acoustic signal, we have used the TC4014 hydrophone which has a frequency response of up to 480 KHz [23]. The receiving sensitivity for such a hydrophone is 186dB ±3dB re 1V/µPa. An active input module (EC6076) is needed to power the hydrophone.

In our experiment, we have first focused on determining the value of t_{wait}, i.e., minimum time required to wait before sending next laser pulse to avoid the effect of vapor clouds. The experimental results are shown in Figure 2. The results indicate that the vapor clouds effect become significant, i.e., high

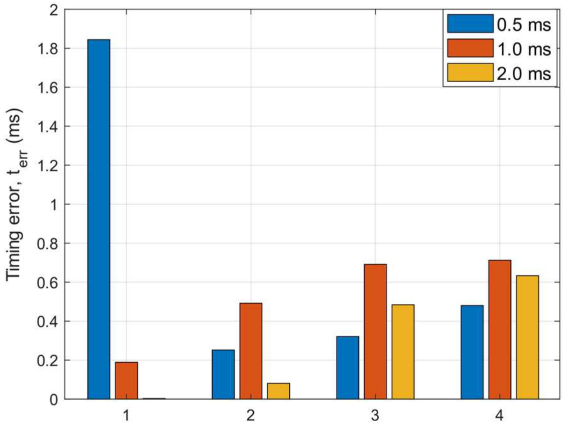

Fig. 10. Relationship between t_p and t_{err}

number of missing acoustic pulses, with the increase in the laser pulse repetition rate, i.e., with the decrease of duration between two consecutives laser pulse. In our experiment, we have found that the maximum repetition rate is 16 Hz or minimum duration between two laser pulses is 62.5 ms for which there is no acoustic pulse missing. Therefore, in our analysis we have used $t_{wait} = 62.5$ ms.

Next, we run an experiment to determine the minimum value of t_p and the corresponding maximum bit-rate gain $A_{PPM/OOK}$. Figure 10 shows the observed t_{err} for three different values of t_p. The experiment is repeated four times. From this figure we can observe that for each experiment, the value of t_{err} is higher or almost equal to t_p for $t_p = 0.5$ ms. For $t_p \geq 1.0$ ms, t_{err} is much less than the corresponding value of t_p which is crucial for successful decoding of received signals as we discussed earlier. Hence, for our PPM frame, the minimum value of t_p is 1.0 ms. From Figure 9, we can see the optimum value of *M* is 4 for $t_p = 1.0$ ms. Therefore, in our frame design we have used *M* = 4. When $t_p = 1.0$ ms and *M* = 4, Figure 8 shows that the bit rate gain of our proposed PPM modulation is 3.2 times higher than the OOK modulation; this is indeed significant improvement in the achievable bit rate over our previously published OOK based modulation [19].

V. Conclusions

The photoacoustic energy transfer mechanism is a promising and effective way to communicate from air to underwater. Yet the lack of proper modulation techniques hinders the realization of such a communication system. Moreover, the generation of vapor clouds at the laser focus point makes it hard to achieve a higher bit rate. In this paper, we have presented a novel PPM based modulation technique which has the capability to avoid generation of vapor clouds by designing an efficient PPM frame. In the frame design, we have carefully added extra time slots to ensure that there are no two consecutive laser pulses less than the minimum duration required to mitigate the effect of vapor clouds. Both simulation and lab experiments have been conducted to validate the effectiveness of our frame design. We have provided guidelines for the setting of crucial parameters to maximize the bit rate. We have also confirmed that our PPM based approach outperforms OOK modulation.

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