Optimized QAM Order with Probabilistic Shaping for the Nonlinear Underwater VLC Channel

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Abstract: We found the optimum QAM order with PS for the nonlinear UVLC channel is not the adjacent integer of entropy. Higher order QAM can outperform adjacent order for 80.57% in net transmission rate.

1. Introduction

To further facilitate the underwater activities such as pollution monitoring, offshore exploration, oceanography research and so on, the increasing number of underwater unmanned devices demands for a growing capacity of the underwater wireless communication (UWC) [1-2]. The existing UWC method mainly includes radio-frequency (RF) and acoustic communication, while the low-bandwidth of acoustic signal and high-attenuation of RF signal underwater restrain their future development. Exploiting the characteristics of low attenuation window of the blue-green-yellow light for seawater, underwater visible light communication (UVLC) attracts more and more attention, especially for the light emitting diodes (LEDs)-based UVLC system due to its advantages of low-cost, eye-safety and the potential of realizing Gbit/s-class transmission. However, narrow modulation bandwidth of the commercial LED and the nonlinear effect induced by the imperfect devices are still the major issues for the high-speed VLC system [3].

In order to overcome such challenges, advanced modulation formats including carrier-less amplitude and phase (CAP) and discrete multi-tone (DMT) modulation, have been successfully used in plenty of beyond Gbit/s-class VLC/UVLC systems, achieving the high spectral efficiency [4-6]. Moreover, probabilistic shaping (PS), which is an emerging constellation shaping technology, can be combined with the advanced modulation formats to approach the Shannon limit (SL) [7-8]. Based on a certain communication channel, the transmission entropy H(A) should be first set to be a constant value which satisfied $n-1 < H(A) < n$. The value of n is integer. Normally, the PS-2^n-QAM can get the best net transmission rate (NTR) under the Additive White Gaussian Noise (AWGN) channel compared with PS-2^{n+1}-QAM, which will be proved in section 2. Nevertheless, the PS-2^{n+1}-QAM may outperform than the PS-2^n-QAM if the UVLC channel is suffering severe nonlinear effect. For example, if n=7, the performance of PS-128QAM and PS-256QAM may be different in nonlinear and AWGN case. This paper will focus on the verification of this hypothesis.

In this paper, the optimum QAM order with probabilistic shaping for the nonlinear Underwater VLC channel is investigated both in simulation and in experiment. We found that in linear AWGN channel, the optimal QAM-order for a best NTR is the adjacent integer of entropy. However, in nonlinear cases, the optimal QAM order is no longer the adjacent QAM order, but the higher order. Regarding about NTR, PS-256QAM can outperform PS-128QAM for 80.57% after a 1.2 m nonlinear UVLC link.

2. Principle

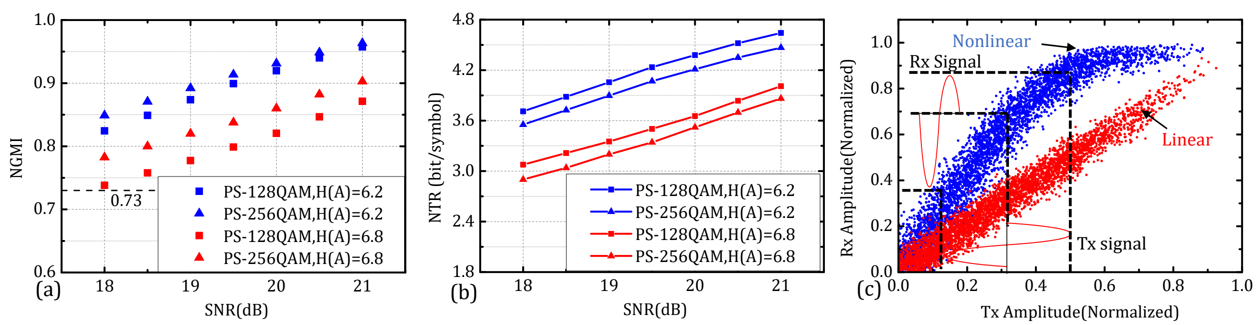

Fig. 1. The SNR versus (a) the NGMI of PS-128QAM and PS-256QAM with the H(A) of 6.2 and 6.8. (b) the NTR of the PS-128QAM and PS-256QAM with the H(A) of 6.2 and 6.8. (c) The linear and nonlinear response of the transmitted signal (Tx) and received signal (Rx) for the UVLC system.

First, we do a simulation to compare the normalized general mutual information (NGMI) and NTR performance of PS-2^n-QAM and PS-2^{n+1}-QAM under the AWGN channel when the H(A) and SL of channel are both between n-1 and n. To make sure our simulation results are universally fit for the any AWGN channel, the range of the SNR is randomly chosen from 18 to 21, which means the minimum and maximum SL of the channel is from 6 to 7 referring to the definition of SL. Besides, the H(A) is also randomly set to 6.2, 6.8 for the PS-2^n-QAM and PS-2^{n+1}-QAM constellation, where n=7. According to above random condition, the NGMI of PS-128QAM and PS-256QAM can be calculated from the equation (6) in Ref. [10] and illustrated in Fig.1(a). Because all of the NGMI is higher than 0.73, the forward error correction (FEC) code rate of the simulation is fixed to 0.73 to make sure an error-free post-FEC result for the simulation. Finally, the NTR of PS-128QAM and PS-256QAM is calculated from the equation (2) in Ref [9] and plotted in Fig.1 (b). The results indicate that the PS-128QAM has the superior performance than PS-256QAM at the same SNR and H(A) in AWGN channel. Due to the randomness of the SNR and H(A), the results fit for any value of n in AWGN channel. Hence, PS-2^n-QAM outperforms the PS-2^{n+1}-QAM constellation in AWGN channel with both the constant H(A) and SL between n-1 and n when an error-free transmission is guaranteed.

However, the severe nonlinear effect always exists in UVLC system due to the high output power of signal and the imperfect response of the devices, because the high output power of the signal is the key method to extend the underwater transmission distance. The nonlinear effect of the UVLC system is clearly observed from the Fig.1 (c). When the signal amplitude is high, the nonlinear effect will distort the amplitude of the signal. That's to say, the out ring of the uniform QAM constellation will suffer more nonlinear damage than the inner constellation when peak to peak voltage (V_{pp}) of the signal is high. Thus, such nonlinear effect may cause above principle in AWGN channel unavailable in UVLC system with nonlinear effect. It's meaningful and necessary to discuss whether PS-2^n-QAM outperforms the PS-2^{n+1}-QAM in the PS-CAP UVLC system with severe nonlinear effect.

3. Experimental Setup

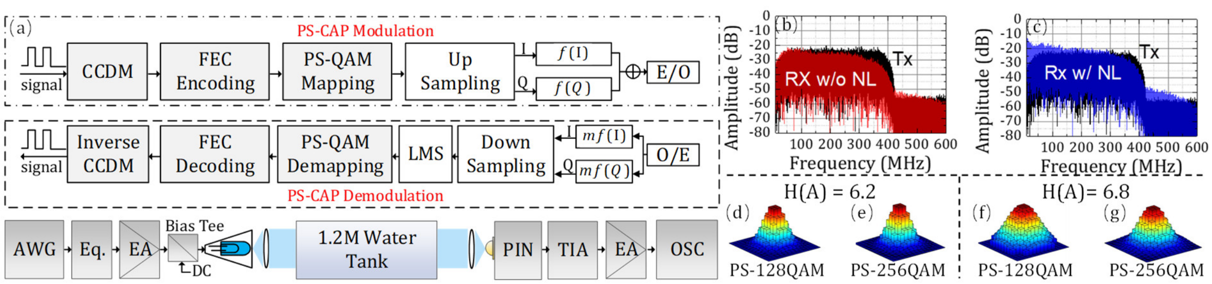

Fig. 2. (a) The experimental setup (Lower) and the flow diagram of the signal generation and offline processing for PS-CAP modulation (Upper). (b-c) The frequency response of the transmitted signal (Tx), received signal without nonlinear effect (Rx w/o NL) and with nonlinear effect (Rx w/ NL).(d-g) Probability distribution of PS-128QAM and PS-256QAM constellation when H(A)=6.2 and 6.8.

Fig2. (a) shows the experimental setup of our VLC system over 1.2 m underwater link. First, the signal sequence is generated by Arbitrary waveform Generator (AWG, Tektronix AWG710b) and then fed into the blue LED after hardware equalization and amplification. The PIN photodiode (HAMAMATSU S6968) is located at the distance of 1.2 m from the LED to detect the optical signal and transform it to the current signal. The current signal is amplified by a Trans-impedence Amplifier (TIA) and an Electric-Amplifier (EA) afterwards. Finally, the amplified signal is recorded by an oscilloscope (Keysight, DSO 9404A) to do offline processing. In our 1.2 m underwater system, the severe nonlinear effect can be clearly observed from the comparison of the frequency response in Fig.2 (b) and (c). Such nonlinear effect results in the more uneven frequency response of the received signal and system's lower SNR.

At the PS-CAP modulation part, the PS-128QAM and PS-256QAM constellation are respectively generated from the uniform 128QAM and 256QAM constellation, utilizing the constant composition distribution matching (CCDM) and the forward error correction (FEC) encoder. In the PS scheme, the I- and Q-component of the PS-QAM constellation match the Maxwell-Boltzmann distribution to adapt the AWGN channel. The probability distribution of the generated PS-128QAM and PS-256QAM constellation with the H(A) of 6.2 and 6.8 are plotted in Fig.2 (d-g). Next, the PS constellation is up-sampled and then spilt into the I- and Q-path to do impulse shaping by a square root raised cosine (SRRC) filter. The roll-off factor of the SRRC filter is 0.205. In this way, PS-CAP signal is finally formed via adding the filtered I- and Q- signal.

At the PS-CAP demodulation part, the received signal is first filtered by a matching filter, and then go through down-sampling. To eliminate the linear noise, a least means square (LMS) filter is used as the post-equalizer. The FEC decoder and inverse CCDM are deployed to recover the signal. Using the recovered signal and transmitted signal, the GMI, NGMI, NTR can be precisely calculated.

3. Results and Discussion

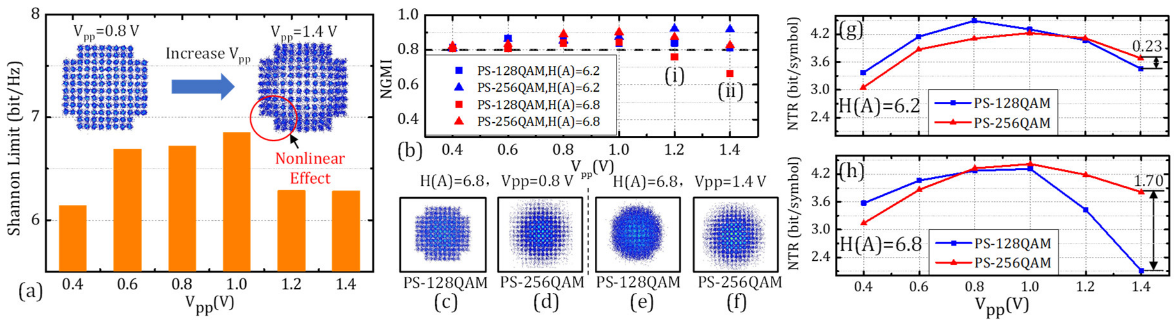

Fig. 3. (a) The SL of the UVLC system at different V_{pp}. The inset is the constellation diagrams of uniform 128QAM at the V_{pp} of 0.8 V and 1.4 V. (b) The measured NGMI of PS-128QAM and PS-256QAM at different V_{pp}. (c-f) The constellation diagrams of the received signal at H(A)=6.8. The NTR of PS-128QAM and PS256QAM with (g) H(A)=6.2. (h) H(A)=6.8.

First, the SL of the UVLC channel at different V_{pp} is depicted in Fig.3(a). When the SNR varies from 0.4 V to 1.4 V, the value of SL is between 6 and 7. As the constellations in Fig.3(a) shows, when the signal V_{pp} is increased to 1.4 V, the nonlinear effect starts to exist in the UVLC system and the out-ring constellation points suffer severe distortion, leading to the increase of symbol error rate. After transmitting the PS-CAP signal over the 1.2 m UVLC system, the corresponding NGMI and NTR of PS-128QAM and PS-256QAM are measured at the H(A) of 6.2 and 6.8, which are same as the simulation. Fig.3(b) shows the calculated NGMI of PS-128QAM and PS-256QAM at different V_{pp}. The NGMI of PS-256QAM and PS-128QAM at all operation points of V_{pp} are above 0.8 except that of the PS-128QAM with the H(A) of 6.8 at 1.2V and 1.4V, which labeled (i) and (ii) in Fig.3 (b). Therefore, the FEC code rate-0.8 can be utilized to calculate the NTR for PS-128QAM and PS-256QAM except points (i) and (ii). To guarantee the error-free transmission for all points, the NGMI of these two points is used as the FEC code to calculate NTR. The NTR of PS-128QAM and PS-256QAM with the H(A) of 6.2 and 6.8 are respectively shown in Fig.3 (g, h). When the signal V_{pp} is above 1.2 V and H(A) is 6.2, the PS-256QAM outperforms PS-128QAM, achieving up to 0.23 bit/symbol NTR enhancement at the V_{pp} of 1.4 V. When the V_{pp} is higher than 0.8 V and H(A) is 6.8, the NTR of PS-256QAM also outperforms PS-128QAM with a gain of 1.70 bit/symbol at the V_{pp} of 1.4 V, which is 80.57% of the NTR of PS-128QAM. The constellation diagrams of received signal at H(A) of 6.8 is shown in Fig.3(c)-(f). As H(A) is close to 7, the high probability of PS-128QAM out-ring constellation points suffer severe nonlinear effect at high V_{pp}, which cause a deterioration of system performance. Meanwhile, the out-ring probability of PS-256QAM is much lower than that of PS-128QAM at the same H(A), which can be observed in Fig.2 (d-g). Therefore, the out-ring constellation points of PS-256QAM suffer less nonlinear deterioration, improving the nonlinear effect resistance of PS-256QAM. These results enhanced the fact that the optimal QAM order with PS is the higher order instead of the adjacent integer of H(A) in nonlinear UVLC system.

4. Conclusions

We investigate the NTR and NGMI performance of PS-QAM constellation in a UVLC channel by simulation and experiment. We first choose the channel with SL range of 6-7 and H(A) of 6.2 and 6.8 randomly. The FEC code rate is chosen to satisfy error-free transmission. In AWGN cases, the optimal QAM order is the adjacent integer of the entropy. In nonlinear cases, the optimal QAM order is not the adjacent order, but the higher order. Experimental results show the NTR can be increased up to 80.57% by using PS-256QAM rather than PS-128QAM over a 1.2 m nonlinear UVLC link.

Acknowledgement

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5. References

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