2.4-Gbps Ultraviolet-C Solar-Blind Communication Based on Probabilistically Shaped DMT Modulation

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Abstract: We present a record-breaking 2.4-Gbps/1-m ultraviolet-C (UVC) line-of-sight (LOS) optical wireless communication link with 2.0 Gbps data rate maintained over 5 m. We also demonstrate a UVC diffuse-LOS link maintained over ± 5.5-degree angle changes. © 2020 The Authors.

1. Introduction

Due to the increasing demand for high-speed wireless communication and the over-crowdedness of the bandwidth of communication based on the radio frequency (RF) technology, the use of optical wireless communication (OWC) as a complementary technology for data transmission has recently been widely adopted in different fields. OWC, in which the signal is transmitted by modulating infrared (IR), visible, or ultraviolet (UV) light, has the advantage of having an unlicensed wide bandwidth, which can be utilized to send data at high speeds without being affected by electromagnetic interference. However, the background noise from sunlight and the strict positioning, acquisition, and tracking requirements pose serious challenges to the reliability of OWC links, which is why solar-blind, deep ultraviolet communication has garnered research attention in the past few years.

Ultraviolet-C (UVC) light, ranging from 100 to 280 nm, coming from the sun is completely absorbed by molecules in the atmosphere, including ozone, oxygen, and carbon dioxide molecules. Using an optical transmitter operating in this wavelength range to send data provides immunity to background noise. Moreover, the high scattering of UVC light alleviates the need for line-of-sight (LOS) transmission. Instead, diffuse-LOS and non-line-of-sight (NLOS) links can be established using UVC light. The aforementioned advantages, as well as the recent development in solid-state UVC light-emitting diodes (LEDs) and high-speed low-cost detectors [1], make UVC OWC a promising communication technology, but maintaining high speeds over practical distances has been a challenge. In [2], a 71-megabit-per-second diffuse-LOS link was demonstrated based on a 294-nm LED operating in the ultraviolet-B (UVB) regime over a short distance of only 8 cm. In 2019, a LOS 1.5-m link was tested in an outdoor environment using a 280-nm LED with a data rate of 1.18 gigabit-per-second (Gbps) [3], and a similar system was used in [4] to establish a 2-Gbps indoor link over 1.5 m. Using a micro-LED emitting light at a wavelength of 262 nm, He *et al.* demonstrated a 1.1-Gbps LOS link, but the distance was limited to 30 cm due to the limited LED power [5]. NLOS links across longer distances based on UVC and photomultiplier tubes (PMTs) have been also demonstrated in numerous works, but with data rates in the kilobit-per-second range. However, our focus here will be on LOS and diffuse-LOS links.

In order to achieve rates close to Shannon limit in an OWC link, probabilistic shaping (PS) [6], which is an emerging cutting-edge constellation shaping scheme, can be combined with bitloading discrete multitone (DMT) modulation for high spectral efficiency. The equally non-equiprobable constellation with an optimal Maxwell-Boltzmann (MB) distribution is individually generated for every subcarrier according to their signal-to-noise ratio (SNR) [7].

In this work, using PS, we demonstrate the fastest UVC LOS link reported to date with an effective achievable information rate (AIR) of 2.4 Gbps over 1-m and an AIR over 2 Gbps maintained over 5 m, which is more than three folds longer than other UVC/B LOS links presented in the literature. We also show a record-breaking 0.82-Gbps AIR for a UVC diffuse-LOS link which receives the signal over a change of ± 5.5 degrees in the relative angle between the transmitter and the receiver, maintaining an AIR above 0.28 Gbps over all angles. The AIR values are calculated after removing the forward error correction (FEC) 11% overhead. These links are established using a 278-nm LED as the transmitter and an avalanche photodetector (APD) as the receiver. This demonstration shows the true potential of UVC in high-speed LOS and diffuse-LOS OWC links by utilizing PS to achieve the channel capacity limit.

2. Experimental Setup

The LOS link was established by placing a commercial UVC LED at a distance of 1 m from an APD (Thorlabs, APD430A2), as shown in Fig. 1(a). The LED has a peak intensity at a wavelength of 278.32 nm. The light coming out of the LED is modulated using an arbitrary wave generator (AWG, Tektronix, AWG710b) followed by an amplifier. The signal detected from the APD is amplified and fed to and recorded on a mixed signal oscilloscope (Agilent, MSO9254A) for offline processing. After testing the system at a distance of 1 m, the transmission distance was increased to 5 m to show the viability of using UVC LEDs in practical OWC applications.

Figure 1(b) shows the modulation bandwidth of the communication link at a distance of 5 m with different injection currents. The 170-MHz -3-dB modulation bandwidth measured for this link allows for high-speed communication, especially considering the slow decay of the response at higher frequencies. This slow decay makes it possible to use frequency division multiplexing (FDM) techniques to utilize frequencies way beyond the -3-dB cutoff frequency.

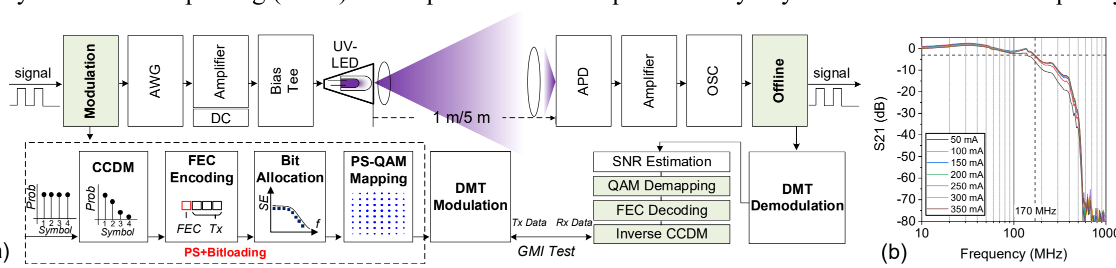

Fig. 1: (a) The experimental setup and the flow diagram of the signal generation and offline processing. (b) The modulation bandwidth of the system at a distance of 5 m with different injection currents.

The channel was tested using DMT [8] to measure the SNR for different subcarriers to implement the most suitable bit allocation. Based on the channel characteristics, a constant composition distribution matching (CCDM) and a FEC encoder are employed to generate I- and Q-path PS-pulse-amplitude-modulation-16 (PS-PAM-16) with an optimal MB distribution. For the PS-QAM symbols generated by the corresponding PS-PAM-16 symbols, the AIR can be calculated by the generalized mutual information (GMI) and the binary FEC code rate of 0.9 in our work, referring to Equation 3 in [9].

3. Results and Discussion

To find the best bias point and signal amplitude, different values were tested by measuring the AIR using both normal and PS bitloading. The results are shown in Fig. 2(a) and 2(b). The highest AIRs for normal and PS bitloading were respectively recorded at injection currents of 250 mA and 300 mA, corresponding to optical powers around 6 and 7 mW, and a signal amplitude of 1 V_{pp}. Different signal bandwidths ranging from 350 to 550 MHz were tested by changing the sampling frequency of the AWG. Figure 2(c) shows the AIR for these signals at a distance of 1 and 5 m.

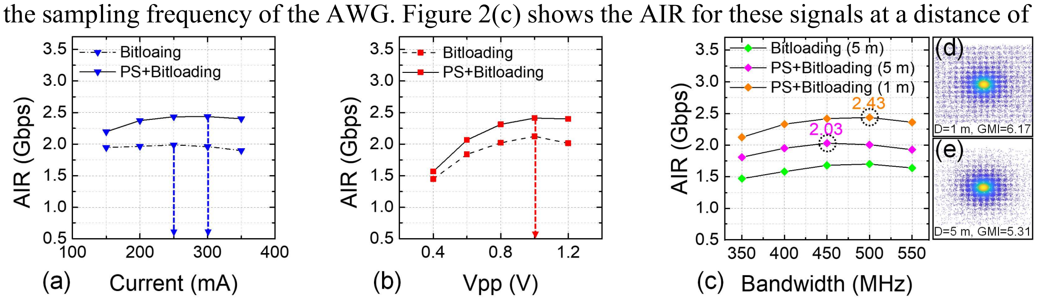

Fig. 2: The AIR at different (a) injection currents, (b) signal amplitudes, and (c) signal bandwidths. The PS constellation diagram at transmission distances of (d) 1 m and (e) 5 m. All AIR values are calculated after removing the 11% FEC overhead.

At 5 m, we measured an AIR of 1.70 Gbps using normal bitloading. However, the AIR is increased up to 2.03 Gbps when PS is used. Moreover, when the link is tested at a distance comparable to previous works in the literature, a record-breaking 2.43-Gbps data rate is achieved. The AIR values reported are calculated after the 11% FEC overhead is removed. The PS constellation diagrams at distances of 1 and 5 m are shown in Fig. 2(d) and 2(e), respectively. The high data rate made possible by the use of PS highlights the potential of UVC OWC as a complementary technology for other communication techniques that provides robustness against background noise in outdoor environments.

Figure 3(a) shows the GMI for the different subcarriers before and after using PS. It is observed that the GMI approaches the Shannon limit of the channel after using PS. The normalized GMI (NGMI) is shown in Fig. 3(b) with a minimum value of 0.91 among all subcarriers, verifying that a rate-0.9 code can produce error-free post-FEC results for our UVC OWC link. Figure 3(c) shows typical constellation diagrams with and without PS at different subcarriers.

To test the performance of the diffuse-LOS link, the collimation lens was moved closer to the LED to make the beam divergent. While this divergence over the 5-m transmission distance decreases the strength of the received signal, it allows the receiver to detect the signal without having to be perfectly aligned with the line of sight of the transmitter. We changed the relative angle between the transmitter and the receiver and recorded the AIR. Around the zero-degree angle, an AIR of 0.82 Gbps was recorded. As the angle is increased, the AIR drops, but near to the edge, it increases again. This increase is due to the nonuniform profile of the beam, which has high intensity in the center and at the outer ring of the beam. The AIR and the received optical power per unit area are shown in Fig. 3(d), while the inset shows the beam profile. We can see that the AIR and the optical power observe the same pattern, which is consistent with the profile of the light beam. The communication link is maintained over a ± 5.5-degree change in the relative angle between the transmitter and the receiver with AIR values over 0.28 Gbps along all angles.

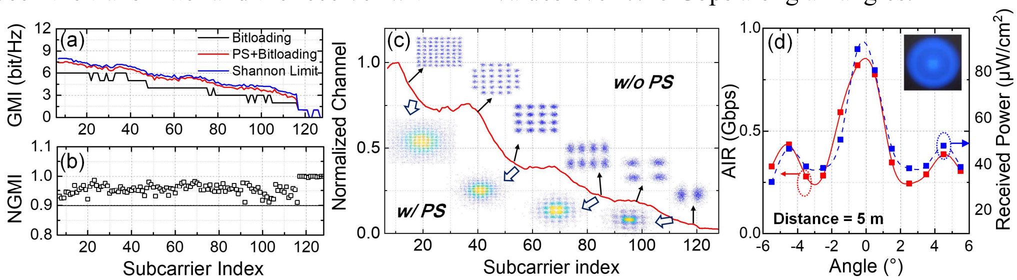

Fig. 3: (a) The GMI for the different subcarriers before and after using PS at a distance of 5 m. (b) The NGMI of the different subcarriers. (c) The constellation diagrams of the received signal with and without PS. (d) The GMI and the received power per unit area of the 5-m diffuse-LOS link at different angles, and the inset is a picture of the beam profile. The 11% FEC overhead was removed in the AIR calculation.

4. Conclusions

The use of a UVC LED in LOS and diffuse-LOS OWC links is demonstrated in this work. A record-breaking AIR of 2.4 Gbps for LOS UVC links is achieved using PS over a distance of 1 m. A 5-m LOS link was also demonstrated with an AIR over 2 Gbps. A high-speed diffuse-LOS link that maintains communication over ± 5.5-degree changes in the relative angle between the transmitter and the receiver is established with a peak AIR of 0.82 Gbps and AIR values over 0.28 Gbps along all tested angles. This demonstration highlights the real potential of UVC OWC in high-speed applications with relieved alignment requirements and immunity to background noise.

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