Theoretical and experimental research on diversity reception technology in NLOS UV communication system

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Abstract: Diversity reception technology is introduced into ultraviolet communication area in this article with theory analysis and practical experiment. The idea of diversity reception was known as a critical effective method in wireless communication area that improves the Gain significantly especially for the multi-scattering channel. A theoretical modeling and simulation method are proposed to depict the principle and feasibility of diversity reception adopted in UV communication. Besides, an experimental test-bed using ultraviolet LED and dual receiver of photomultiplier tube is setup to characterize the effects of diversity receiving in non-line-of-sight (NLOS) ultraviolet communication system. The experiment results are compared with the theoretical ones to verify the accuracy of theoretical modeling and the effect of diversity reception. Equal gain combining (EGC) method was adopted as the diversity mechanism in this paper. The research results of theory and experiment provide insight into the channel characteristics and achievable capabilities of ultraviolet communication system with diversity receiving method.

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References and links

1. Introduction

Atmospheric scattering of ultraviolet (UV) radiation makes it possible to establish a non-line-of-sight (NLOS) communication link and which is a candidate for free-space optical communication (FSO) suitable for radio-silent condition as described in [1–3]. Relevant UV communication experiments have been conducted in recent years, include UV LD/LED for transmitter and UV APD/PMT for receiver [4–8]. However, the performance of these test system were constrained by varied limitations. Such as the signaling rates (20–400kHz), channel bandwidth (within Mbps) and link distance (hundred Meters) with lamps, flashlamps or lasers for transmitter and even low parameters with LED. Researchers in UV communication area are continuously looking for the effective method and techniques to improve the transmission performance of the UV communication system [9–14].

It is the atmospheric scattering makes the UV technology possible for NLOS communication but the same reason for the deteriorate performance for communication. We found that there are many similarities with UV channel and Radio Frequency channel, so we considered whether the typical techniques in 3G/4G wireless communication that proved effective were suitable for UV communication system, such as diversity reception technology. The wireless communication system can obtain diversity gain by increasing the amount of antenna in receiver in a fading environment [15].

In this paper, we present the study of the effects of diversity reception technology in UV communication system both in theoretical analysis and experimental verification. The theory model of diversity reception for UV communication system is described in Sec. 2, and the effect of diversity receiving method with multi-receiver is depicted as well. We get proved results from experiments on our UV LED/dual PMT receiver test-bed described in the third part. Using a pair of high speed PMT and diversity algorithm logical module, we measured the BER, Signal Receiving Gain and Baseline Separation Distance of the Dual-PMT receiver incorporating different elevation angles and separation distance. The results and conclusion part show the diversity reception technology can be taken as a critical method for optimizing the performance of UV communication system. These measurements provide an effective way to improve channel capacity, achievable signaling rates and transmission distance, and make the UV communication system suitable for more practical transmission requirements and complicated surroundings.
2. The theoretical analysis of diversity reception in UV communication

2.1. Simulation platform and diversity algorithm

A multi-receiving simulation platform was established with MATLAB to study the effects of diversity receiving. Our planar communication geometry is shown in Fig. 1. We define parameters as follows. Let \( \alpha_1 \) be the Tx beam full-width divergence, \( \alpha_2 \) the Rx FOV, \( \beta_1 \) the Tx apex angle, \( \beta_2 \) the Rx apex angle, and \( R \) the Tx and Rx separation distance, respectively. Equal gain combining (EGC) has been used for diversity receiving method, because it’s easier to achieve comparing with maximal ratio combining (MRC) and provide better performance than selective combining (SC) [15].

\[ SNR = \frac{\left( \sum_{i=1}^{M} r_i \right)^2}{\sum_{i=1}^{M} N_i} = \frac{1}{MN} \left( \sum_{i=1}^{M} r_i^2 + \sum_{i,j=1}^{M} r_i r_j \right), \]

Note that the average signal to noise ratio is modeled as

\[ \overline{SNR} = \frac{1}{MN} \left( \sum_{i=1}^{M} \overline{r_i^2} + \sum_{i,j=1}^{M} r_i r_j \right), \]

where \( \overline{r_i r_j} = r_i \cdot r_j \) if branches are noncorrelation. If the receivers meet the non-correlation condition, the transmission channels are mutual independent. We can get many different signal copies because of the signal fading is independent. Diversity reception technology could use these signal copies to recover the signal and get a better performance. The ultraviolet beam separates into several units of Fresnel zone in free space [16] and the diameter of these units named Fresnel size. Let \( \rho_d \) be the size of these Fresnel zone by \( \rho_d = \sqrt{\lambda R} \). The noncorrelation condition is given by

\[ \sqrt{\lambda R} < d < \theta R, \]

where \( d \) is the separation distance of PMTs, \( \lambda \) is the wavelength, \( R \) is Tx and Rx baseline separation, and \( \theta \) is beam full divergence. For example, the ultraviolet wavelength we used in solar blind zone is 265nm and separation distance is 1000 meters. We have \( \sqrt{\lambda R} \approx 0.01m \) by using Eq. (3).
Study [17] indicates that the number of photon counts recorded using a photon counter is random and follows a Poisson distribution. Define the photon arrival rate as $\gamma$, and $P_l = N_p \gamma$ is the received light power. $I_l = \eta P_l \lambda / hc$ is the photocurrent where $E_p$ is each photon energy. $N_p$ is photon count, $\eta$ is the PMT detected efficiency, c is the speed of light, and h is Planck’s constant. It is a linear relationship between the received light power and photocurrent, so amplitude of the signal follows Poisson distribution as well. Consequently, $r_i^2 = \gamma^2 + \gamma$, and $r_i \cdot r_j = \gamma \cdot \gamma = \gamma^2$. We can obtain the average SNR as

$$SNRP = \frac{1}{MN} [M(\gamma + \gamma^2) + M(M-1)\gamma^2]$$
$$= \frac{\gamma + \gamma^2}{N} [1 + (M-1) \frac{\gamma^2}{\gamma + \gamma}]$$
$$= \frac{SNR_0[1 + (M-1) \frac{1}{1 + \frac{1}{\gamma}}]}{(4)}$$

$$\frac{SNRP}{SNR_0} = 1 + (M-1) \frac{1}{1 + \frac{1}{\gamma}}.$$

Define the photo arrival rate as $\gamma = \gamma_s + \gamma_n$. The signal noise ratio without diversity method at the receiver is modeled as

$$SNR_0 = \frac{\gamma_s}{\gamma_n}.$$  (6)

where $\gamma_s$ is the ratio of the signal photon arrival rate at the receiver during the pulse signaling period and $\gamma_n$ is the noise count rate.

We just consider medium noise condition instead of low nor high noise condition. With a 200$\mu$s pulse width, the medium noise condition gave rise to measured 0.95 photon counts per pulse, equivalent to the noise count rates $\gamma_n$ of 4.75KHz respectively. It is straightforward to show that [18]

$$\gamma_s = \frac{\eta P_l}{LR_b \frac{hc}{\lambda}} = \frac{\eta P_l \lambda}{LR_b hc},$$  (7)

where $R_b$ is the bit rate and $L$ is the path loss. The path loss is modeled as

$$L = \xi R^\alpha,$$  (8)

where $\xi$ is the path loss factor and $\alpha$ is the path loss exponent. From Eq. (5), we find SNR increasing depends on the quantity of receiver branches and photon arrival rate. Then the BER may be calculated as a function of SNR using the Q-function

$$BER = Q(\sqrt{SNR}).$$  (9)

Next we use our results to predict the effects of path loss, communication range, transmitted optical power and data rate in terms of BER.

2.2. Simulation results and analysis

Based on G. Chen et al. [18] experimental results and diversity receiving method analysis, we predict a better BER performance of the system. Path loss directly impacts BER performance since it affects $\gamma_s$. Their correspondence is demonstrated in Fig. 2 without diversity reception method(M=1) and with dual diversity receiver(M=2). In our simulation, we have scaled the
power between the two cases (M=1 and M=2) from Eq. (7). The received power is photo arrival rate multiply by photon energy. Here the Tx optical power is 43mW and data rate is 5 Kbps. BER varies rapidly at low path loss, and converges to 0.5 as path loss increase to infinity. From these curves, we can easily find the BER performance is better than the previous one that without diversity reception technology.

As an example with realistic system parameters, let UV LEDs emit 43mW optical power, the Tx and Rx apex angles be 20°, and a data rate of 5 Kbps. Figure 3 shows BER performance against distance without diversity receiver and with dual diversity receiver case. The path loss exponent at these apex angles is 1.9139 and path loss factor is 3.43 × 10^5 [18]. These numbers translate into path loss as a function of distance using Eq. (8). BERs are sensitive to distance when the distance is short, and converge to 0.5 at a large baseline separation. Note that the BER changes by a few orders of magnitude when R increases from 10m to 20m in this scenario, but the performances of diversity receiving method are better with nearly 2.5dB.
Transmitted optical power has an effect on BER that is similar to that from the inverse of path loss. In Fig. 4, we vary the Tx optical power $P_t$ from 1mW to 1000mW (only for simulation) and show BER versus $P_t$ for different distances. Assume the Tx and Rx apex angles are fixed at 20° (giving path loss exponent 1.9139), data rate of 5 Kbps, Tx and Rx baseline separation of 40 meters and a medium noise environment. Similar with the results above, the dual diversity receiver has better performance in Fig. 4 and the transmission distance achieve 40 meters with lower optical power in the same data rate.

BER performance and communication data rate also provide a trade-off with other fixed parameters: the lower the data rate, the lower the BER. Here we consider one pulse per bit and vary the data rate from 1 bps to 1 Mbps by varying pulse width $T_p$ from 1s to 1μs, in the medium noise case. Figure 5 depicts BER versus data rate for different distances (10m, 100m). For a given distance, although the BER typically varies by five orders of magnitude...
while the data rate varies by only one order, diversity reception technology improves the BER performance significantly. That means UV communication system with diversity receiver can achieve higher data rate for a given distance and BER requirement, or achieve lower BER for a given data rate and distance.

3. The Dual-PMT diversity receiver experiment setup

3.1. The architecture of the test-bed and experimental conditions

The architecture of LED-based UV communication test-bed with dual-PMT is depicted in Fig. 6. It is a typical diversity reception architecture includes an arrayed-LED UV source, a pair of high sensitivity PMT detector and logical module that operating diversity algorithm.

![Fig. 6. LED-based UV communication test-bed with dual PMT: Transmitter location is indicated by A; Receiver was placed at various ranges along the path indicated by the line.](image)

All experiments were operated on the solar blind UV communication test-bed and all measurements were taken in an open field at the Beijing University of Posts and Telecommunications stadium, under clear skies on a sunny day in beginning April of 2012. We fixed the beam divergence at a full 7° and all detectors FOV at 30°. The time interval was from 9 AM to 16 PM. The high and low temperatures were about 10°C and 18°C respectively, wind speed was 28 kilometers per hour, and humidity was below 21%. The molecular distribution was assumed relatively stable. And the aerosol distribution was appropriately 1200 per cm³ [19]. Different atmospheric conditions on the UV communication link were not yet considered in our experimental measurements and analysis.

3.2. Construction of transmitter

The transmitter was a LED-based UV communication component working in the solar blind band. The optical source is a LED array with 36 UV LED chips (UV TOP 260 TO 3 HS with nominal center wavelengths of 265 nm, SETI corp. That encapsulated with Hemispherical Lens). Though the UV source is an arrayed-LED, it is obviously isotropy and comes from the same signal. A FPGA module was used for feeding binary PN sequences to current driver circuitry that powered the LED array. We modulated each pulse to 2us in width. So the LED could receive a maximum driving current of 2A, yielding an optical power up to 43mW.
Meanwhile, we introduced the small duty cycle to increase the input current and power of give out light of single LED chip (Duty cycle=1%, Maximum Input Current=200mA, Emitting Power=3.6mW). Finally, we got the control current of LED array as 1.2mA, and the emitting power of transmitter as 34.6mW, that could be captured easily and amplified to 30000 times by PMT in receiver. A signaling generator was designed by a FPGA module which accomplished the voice quality test, bit error rate analysis, signal coding and modulation as well. The test system carried the compact voice signal with the rate of 2.4Kbps to 9.6Kbps. And the RS (18, 10) coding with error corruption 2/9 was adopted to overcome the stochastic and avoid the burst error. The modulation part adopted OOK and PPM that suitable for UV channel. Also, the pseudo-random sequence generator was embedded into the FPGA for the open-loop BER performance test.

3.3. Construction of receiver

The logical module in the receiver side operating the noise, filtering, diversity algorithm, demodulation, de-coding and O/V recovery on a FPGA chip showed in Fig. 6.

At the receiver, we considered both vertical and lateral position of the two PMT detectors. Two PMT detectors with built-in preamplifier were fixed onto optical knighthead respectively while the single PMT gain is $10^5 - 10^7$ from Hamamatsu whose response time is about 6 with an active diameter of 8mm. For this study, we employed a solar-blind filter combined with each PMT for photon detection. The solar blind filter was placed in front of the sensing window of one HAMAMATSU PMT module R7154 (side-on type) spectral response from 160nm to 320nm. It is obviously that the transmittance of filter at the receiver is function of the incident angle, so we employed a narrow band interference filter with the center wavelength of 266nm, FWHM 12nm and the peak transmission of 20%. This kind of filter is extremely angle sensitive, by a special optical filter transmittance measurement. We would estimate its FOV to be nearly 30°. The spectrum matched between the LED and the filter. The PMT has a rectangular sensing window with 24 × 8mm, resulting in an active detection area of 1.92 cm². The nominal quantum efficiency of PMT was 30% at 265nm. The effective FOV of the two detector was estimated to be about 30 affected by the dimension of filter and PMT. The moving average filters are used to removing a vast amount of similar normal distribution noise after PMTs for improving the ratio of signal to noise.

The PMT output current was combined in an equal-gain combiner and then forwarded to an open-loop bit error tester based on FPGA. Rotation optical platforms were used to regulate both azimuth and zenith angular at the Tx and Rx. The FPGA Tx used producing $10^6$ bits PN sequence successively (2 × $10^4$ bits for 50 times). In front of each sequence there would be 32 bits preambles and start flag which were used for data synchronisms at the Rx. The error bit counter embedded in the receiver FPGA displayed the BER results at the end of one PN sequence receiving via the serial port.

4. Experimental results and performance analysis

In this section, we present the performance of dual diversity receiver by comparing its experimental and analytical results.

4.1. Tx optical power versus distance

Study [17] indicates that, the transmitted optical power has an effect on BER and it’s similar to that from the inverse of path loss. And path loss follows square-law power decay as a function of Tx and Rx separation distance. As we increase the separation distance, and in order to keep the BER constant ($10^{-4}$), we need to improve the SNR or instead we need to increase the optical output power $P_t$. It can be observed in Fig. 7 that when in the LOS case, the data
rate of 2.4Kbps, although the simulated results and the experimental data show the same trend for this study case, there is still quite significant difference between the simulated Tx optical power and measured Tx optical power. The main reason causing the difference in the optical output power maybe is due to the different noise condition in the experimental measurement and simulations. For the experiment, it is difficult to keep the noise count rate the same as the simulation’s noise count rate. This may result in the difference of an order of magnitude in optical output power between simulation and experiment. Meanwhile, it is notable that the diversity receiving method has a better performance.

4.2. Tx/Rx apex angle versus distance

Tx/Rx apex angles directly affects communication distance since it impacts path loss. Figure 8 plots the communication distance versus Tx/Rx pointing angle pairs at a BER of $10^{-4}$. The experimental results are obtained by first setting the Tx/Rx pointing angle pairs to (0, 0), (10,
10), (20, 20), and (30, 30). We adjust and record the distance between the Tx and Rx while keeping a constant BER of $10^{-4}$. It is apparent in Fig. 9 that at the optical output power of 43mW and the data rate of 2.4Kbps, the dual diversity receiver can work at a further distance than by using the single receiver. As it is evident from Fig. 7 that all the curves show a similar trend and again, the differences in magnitude are due to the simulation conditions just consider the background radiation and path loss without system noise.

5. Conclusion

We presented the feasibility of diversity reception technology using in non-line-of-sight ultra-violet communication system based on theoretical analysis and experiment testing. The theoretical analysis is focus on the critical parameters of diversity reception with multi-receiver, and the simulation platform was verified suitable for the UV communication system. The effect of diversity receiver was studied by BER, SNR for different experiment parameters, including Tx and Rx elevation angles, cross angle, and baseline distance. We found the diversity effect was weakly dependent on cross angle of the PMT, but changed almost linearly with other parameters. And the multi-receiver architecture was proved effective experimentally. These findings provide valuable experimental data for NLOS UV communication system design and performance improvement.

Further work based on diversity reception technology will develop a multi-PMT receiver with 3-4-5 PMT separately, and compare the performance of them to get the optimal receiver architecture. Moreover, we will focus on other techniques in diversity effects, and find more feasible method to improve the system performance of NLOS UV communication, such as MRC(maximum ratio combining) method, which is able to obtain the best performance theoretically.

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