Journal of Science and Engineering Technology, Vol. 16, No. 1, pp. 11-19 (2020)

Receive Diversity with Multiple Photon-Counting Receivers in Non-Line-of-Sight Optical Wireless Communication

WEI-CHIANG WU
Department of Electrical Engineering, Da-Yeh University
No. 168, University Rd., Dacun, Changhua 51591, Taiwan, R.O.C.
wcwm53@mail.dyu.edu.tw

ABSTRACT

To improve the received signal quality in ultraviolet non-line-of-sight optical communication channels, we propose two receive diversity schemes, one with a single optical transmitter and the other with multiple photon-counting receivers. The symbol-level decision fusion scheme is hard decision-based, and each photon-counting receiver sends its local decision to a common receiver. The common receiver makes a final decision according to the majority voting rule. Alternatively, the chip-level data fusion scheme is soft decision-based, and each local receiver sends its observed value directly to the common receiver. The common receiver combines these values and makes a final decision. We determine the symbol error rate of both schemes for *m*-ary pulse-position modulation using the Poisson channel statistic. Performance of both schemes under different scenarios was extensively evaluated using computer simulation. Simulation results demonstrated that compared with a conventional single-receiver system, both schemes exhibit considerable improvement in performance.

Key Words: *M*-ary Pulse-position modulation (MPPM), Symbol error rate (SER), Non-Line of Sight (NLOS), Poisson statistic, Diversity

在無線光通信非視線傳輸系統中使用多個光子量測器之接收分集技術

武維疆
大葉大學電機工程學系
51591 彰化縣大村鄉學府路 168 號
wcwm53@mail.dyu.edu.tw

摘　要

在紫外線非視線傳輸光通信系統中，為了增進接收信號之品質，我們提出了兩種接收分集架構，其中包括了一個光發射器與多個光子量測接收器。符元階層決策合成架構是基於硬式決策法則，每個光子量測接收器獨立做出決策並將其結果傳到共同的接收器。共同的接收器再根據多數法則做出最終的決策。第二種架構則是基於軟式決策法則，每個光子量測接收器將片元

階層所收集到的數據直接傳送到共同的接收器。共同的接收器再根據這些傳送來的數據做出最終的決策。考慮 *M*-ary 脈波位置調變（MPPM）在布阿松統計特性之通道下，我們推導出上述兩種架構之符元錯誤率（SER），此外，我們利用電腦模擬在不同的環境下兩種架構之性能。模擬之結果證實了與傳統單一接收機系統比較起來，兩種架構均提供了可觀的性能增益。

關鍵詞：*M*-ary 脈波位置調變（MPPM），符元錯誤率（SER），非視線傳輸（NLOS），布阿松統計特性，分集

I. Introduction

In future communication networks, optical wireless system serves as a good candidate for its large transmission bandwidth and no electromagnetic radiation compared to the radio system. Recently, ultraviolet (UV) based technology for non-line-of-sight (NLOS) optical wireless communication has received a lot of interest [4, 5, 9]. However, due to the high path loss, the communication range of UV NLOS is inevitably short. To tackle this problem and improve the reliability of the received signal, two approaches may be employed: relaying and receive diversity. The relaying technology aims to transmit the information via intermediate nodes to realize the cooperative communication. In the work of [5], a serial relayed link has been proposed for end-to-end optical wireless communication. While in [2], a count-and-forward relay framework is developed to transmit on-off keying (OOK) modulated optical signals in NLOS optical wireless communication system. The aim of this paper is to develop a simple yet reliable receive diversity framework in NLOS channel, in which the same information received by a number of receivers are combined to enhance the received signal quality. It has been examined in [1], due to the weak link nature of the UV NLOS optical communication channel, the received signal exhibits the characteristics of discrete photons. Thereby, the performance analysis in this paper follows a classical model, i.e., intensity modulated and direct detection (IM/DD) which is also referred to as a photon counting receiver. Pulse-position modulation (PPM), in which information is represented by the position of laser pulse, is a widely-applied technique for transmitting information over the optical direct-detection channel [6]. Each *M*-ary PPM (MPPM) symbol, in which $M = 2^l$ and l is the number of bits conveyed by a symbol, is composed of M time slots. Slot and symbol-level synchronizations are required at the receiver front end, and the MPPM symbol can be determined by choosing among the M time slots with the largest energy. In the work of [3], a single transmitter and multiple receivers, which is referred to as a single-input multiple-output (SIMO) system has been developed for optical wireless NLOS scattering communications. The authors propose a linear minimum mean square error (LMMSE) receiver based on photon-counting detection. Though the complexity is linear with the number of detectors, however, to calculate the LMMSE weight vector requires complicated matrix inverse. This paper considers a SIMO system with single optical transmitter and multiple optical receivers. We propose two receive diversity schemes for improving reliability in a NLOS UV channel: symbol-level decision fusion and chip-level data fusion, in which we refer to as scheme 1 and scheme 2, respectively. Assuming multiple photon counting receivers and MPPM modulation, we derive the average symbol error rate (SER) of both schemes based on the Poisson channel model. In scheme 1, each of the photon counting receiver demodulates the received MPPM signal determines which symbol is sent by the transmitter. The local decision result is then transformed into $l = \log_2 M$ bits and reported to a common receiver. Based on the collected reports from all local receivers, the common receiver makes a final decision according to the majority voting rule. While in scheme 2, local decision is no longer needed, each photon counting receiver just sends the observed photons at each time slot to the common receiver. The common receiver forms a decision statistic based on the observations sent from all local receivers, there then, makes a final decision. Performances of both schemes under different scenarios are extensively evaluated by computer simulation. The results show significant performance gain over conventional single receiver system. The rest of this paper is organized as follows. In Section II, we describe the system model and formulate the problem. Section III describes and analyzes the proposed two receive diversity schemes with multiple photon counting receivers and MPPM. In Section IV, we demonstrate the system performance and discuss the numerical results. Concluding remarks are finally made in section V.

Notation: $\binom{K}{x}$ stands for the combination of *x* out of *K*, $\binom{K}{x} = \frac{K!}{x!(K-x)!}$. $X \sim Po(\lambda)$ means that random variable *X* is Poisson distribution with parameter λ.

II. Signal and System Model

We consider a NLOS UV communication system. Due to the weak received signal nature of the NLOS communications, the received signal exhibits a characteristic of discrete particles, which satisfies a Poisson distribution [3]. In this paper, the received number of photons is assumed to be Poisson random variables for both the detected signal and the detected background fields. As described by [7], this assumption is valid whenever a large number of space-time modes are observed and is generally true for signal-plus-background radiation under nominal operating conditions. Hence, the probability that there are *n* photons at a specific time slot (or chip) in which a laser pulse is absent or present can be obtained, respectively, as

$$P(N=n) = \frac{K_b^{\,n}}{n!} e^{-K_b}; n = 0,1,2,\ldots \quad \text{(background radiation only)} \tag{1}$$

$$P(N=n) = \frac{(K_s+K_b)^n}{n!} e^{-(K_s+K_b)}; n = 0,1,2,\ldots \quad \text{(signal plus background radiation)} \tag{2}$$

where we denote an average of $K_b = \lambda_b \tau$ photons in the background field (noise) and $K_s = \lambda_s \tau$ photons for a laser pulse. Here, λ_b and λ_s denotes the noise and signal intensity in photons/second, respectively. The intensity (counting rate) of the Poisson counting receiver is given by [3]

$$\lambda = \frac{\eta P_t}{L_p h \upsilon} \tag{3}$$

where $\eta, P_t, L_p, h,$ and υ denote the quantum efficiency of the detector, transmission power in one pulse, path loss between the transmitter and receiver, Planck's constant, and the frequency of the optical field, respectively. We consider a single optical transmitter and *K* optical wireless receivers. Hence, it is indeed a SIMO or a receive diversity system. Furthermore, we assume the received number of photons at each receiver is independent.

In this paper, MPPM modulation scheme is considered, in which *l* bits are mapped into one of $M = 2^l$ possible symbols and each symbol is represented by a single laser pulse that is placed in one of the *M* time slots (chips). Let T_s denotes the symbol duration and τ denotes the duration of the MPPM chip, thus $T_s = M\tau$.

III. Performance Analysis of the Proposed Photon Counting Receivers

1. Performance of The MPPM Photon Counting Receiver

In MPPM scheme, each symbol is represented by placing single laser pulse in unique position within one of *M* possible time slots. Let hypothesis *i*, denoted by H_i; *i*=1,…, *M*, be the hypothesis that the laser pulse is allocated at the *i*th time slot, we assume equal *a priori* probabilities, that is $P(H_1) = \cdots = P(H_M) = \frac{1}{M}$. Let n_i; *i*=1,…, *M*, be the photon count at the *i*th time slot, maximum likelihood (ML) decision rule is optimum due to equal *a priori* probabilities assumption

$$H_i^* = \arg \max_{i \in \{1,\ldots,M\}} n_i \tag{4}$$

To derive the correct detection probability, we first calculate the probability of correct detection provided that H_1 is true, $P(C|H_1)$. Thus, at the receiving end, the first time slot includes laser pulse plus background radiation and the remaining (*M*-1) time slots contains background radiation only. We refer the first and the remaining time slots as signal and noise time slot, respectively. Moreover, according to the model as depicted in (1) and (2), the number of detected photons at the signal and time slots is Poisson distributed with parameters $(K_s + K_b)$ and K_b, respectively. To calculate $P(C|H_1)$, it is essential to consider the following events:

A. One or more photons are detected in the first time slot (signal slot) and the noise slots has fewer detected photons than the photons of the signal slot. That is, we need to calculate the probability

$$P_a\left(C\middle|H_1\right)=P\left(n_1\geq 1,n_2,\ldots,n_M<n_1\right) \quad (5)$$

From (1) and (2), we can deduce $P_a\left(C\middle|H_1\right)$ as

$$\begin{aligned}P_a\left(C\middle|H_1\right)&=\sum_{n_1=1}^{\infty}\frac{\left(K_s+K_b\right)^{n_1}}{n_1!}e^{-\left(K_s+K_b\right)}\left(\sum_{j=0}^{n_1-1}\frac{\left(K_b\right)^j}{j!}e^{-K_b}\right)^{M-1}\\&=e^{-\left(K_s+MK_b\right)}\sum_{n_1=1}^{\infty}\frac{\left(K_s+K_b\right)^{n_1}}{n_1!}\left(\sum_{j=0}^{n_1-1}\frac{\left(K_b\right)^j}{j!}\right)^{M-1}\end{aligned} \quad (6)$$

B. There are l out of (M-1) noise slots have exactly n_1 detected photons and the remaining (M-1-l) noise slots have less than n_1 detected photons. Please note that l out of (M-1) noise slots that have exactly n_1 detected photons can occur in $\binom{M-1}{l}$ different ways. In this case, a correct decision is no longer guaranteed since except for one signal slot, there are l noise slots have n_1 detected photons. In what follows, a random choice among (l+1) possible hypotheses yields a correct decision probability equals to $\frac{1}{l+1}$. Thus, the probability of correct decision stemming from this situation can be obtained as

$$\begin{aligned}P_b\left(C\middle|H_1\right)&=\sum_{l=1}^{M-1}\frac{1}{l+1}\binom{M-1}{l}\sum_{n_1=1}^{\infty}\frac{\left(K_s+K_b\right)^{n_1}}{n_1!}e^{-\left(K_s+K_b\right)}\\&\left(\frac{K_b^{\,n_1}}{n_1!}e^{-K_b}\right)^{l}\left(\sum_{j=0}^{n_1-1}\frac{\left(K_b\right)^j}{j!}e^{-K_b}\right)^{M-1-l}\\&=\sum_{l=1}^{M-1}\frac{1}{l+1}\binom{M-1}{l}\sum_{n_1=1}^{\infty}\frac{\left(K_s+K_b\right)^{n_1}}{n_1!}\\&\left(\frac{K_b^{\,n_1}}{n_1!}\right)^{l}\left(\sum_{j=0}^{n_1-1}\frac{\left(K_b\right)^j}{j!}\right)^{M-1-l}e^{-\left(K_s+MK_b\right)}\end{aligned} \quad (7)$$

C. All the M time slots (including signal slots and noise slots) have zero detected photon counts. Here a random decision among M equally likely hypotheses is made, resulting in a contribution to the probability of correct decision of

$$P_c\left(C\middle|H_1\right)=\frac{1}{M}e^{-\left(K_s+K_b\right)}\left(e^{-K_b}\right)^{M-1}=\frac{1}{M}e^{-\left(K_s+MK_b\right)} \quad (8)$$

For symmetry, the overall correct probability can be calculated by combining (6)~(8), which yields

$$\begin{aligned}P(C)&=\frac{1}{M}\sum_{i=1}^{M}P\left(C\middle|H_i\right)=P\left(C\middle|H_1\right)\\&=P_a\left(C\middle|H_1\right)+P_b\left(C\middle|H_1\right)+P_c\left(C\middle|H_1\right)\\&=\frac{1}{M}e^{-\left(K_s+MK_b\right)}+e^{-\left(K_s+MK_b\right)}\sum_{n_1=1}^{\infty}\frac{\left(K_s+K_b\right)^{n_1}}{n_1!}\left(\sum_{j=0}^{n_1-1}\frac{\left(K_b\right)^j}{j!}\right)^{M-1}\\&+e^{-\left(K_s+MK_b\right)}\sum_{l=1}^{M-1}\frac{1}{l+1}\binom{M-1}{l}\times\\&\sum_{n_1=1}^{\infty}\frac{\left(K_s+K_b\right)^{n_1}}{n_1!}\left(\frac{K_b^{\,n_1}}{n_1!}\right)^{l}\left(\sum_{j=0}^{n_1-1}\frac{\left(K_b\right)^j}{j!}\right)^{M-1-l}\\&=e^{-\left(K_s+MK_b\right)}\left\{\begin{array}{l}\frac{1}{M}+\sum_{n_1=1}^{\infty}\frac{\left(K_s+K_b\right)^{n_1}}{n_1!}\times\\\left[\begin{array}{l}\sum_{l=0}^{M-1}\frac{1}{l+1}\binom{M-1}{l}\times\\\left(\frac{\left(K_b\right)^{n_1}}{n_1!}\right)^{l}\left(\sum_{j=0}^{n_1-1}\frac{\left(K_b\right)^j}{j!}\right)^{M-1-l}\end{array}\right]\end{array}\right\}\end{aligned} \quad (9)$$

2. Analysis of the Proposed Detection Schemes

Let the average photons of the background field (noise) received at each photon counting receiver be the same, which is denoted by K_b, and the average photons for a laser pulse received at each photon counting receiver be denoted by $K_{s,1},K_{s,2},\cdots K_{s,K}$, respectively, which depends on the parameters as depicted in (3). Then the correct detection probability of the ith photon counting receiver should be modified from (9) as

$$\begin{aligned}&P_i\left(C\right)=e^{-\left(K_{s,i}+MK_b\right)}\times\\&\left\{\begin{array}{l}\frac{1}{M}+\sum_{n_1=1}^{\infty}\frac{\left(K_{s,i}+K_b\right)^{n_1}}{n_1!}\times\\\left[\sum_{l=0}^{M-1}\frac{1}{l+1}\binom{M-1}{l}\left(\frac{\left(K_b\right)^{n_1}}{n_1!}\right)^{l}\left(\sum_{j=0}^{n_1-1}\frac{\left(K_b\right)^j}{j!}\right)^{M-1-l}\right]\end{array}\right\}\end{aligned} \quad (10)$$

Two detection schemes are proposed in this paper: decision fusion (symbol-level processing) and data fusion (chip-level processing). In decision fusion scheme, every photon counting receiver first performs its own local detection independently. After making a decision among $\{H_i\}_{i=1,2,\ldots,M}$, each receiver forwards its decision to a common receiver and the common receiver makes final decision based on the majority rule. Alternatively, in the data fusion scheme, the common receiver first adds the observed photons at each time slot of photon counting receivers, and the ML decision rule is then performed to decide which hypothesis is true. The block diagrams of the proposed two detection schemes are shown in Fig. 1 and Fig. 2, respectively.

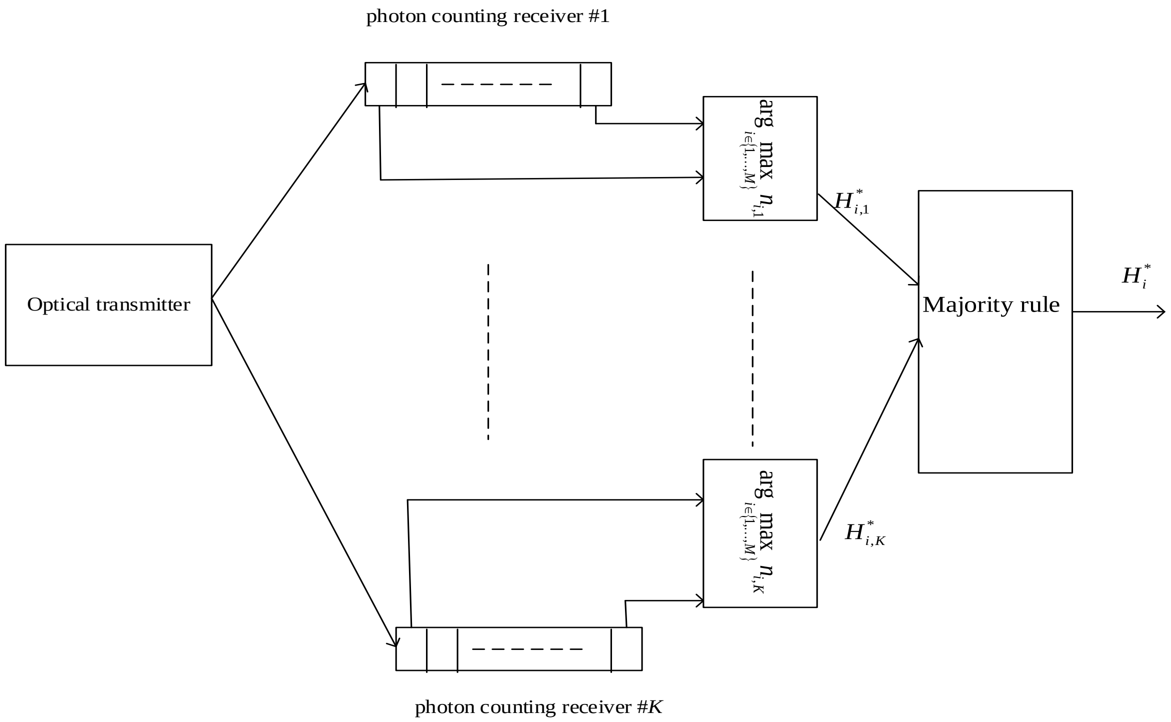

Fig. 1. Scheme 1: Symbol-level processing by decision fusion

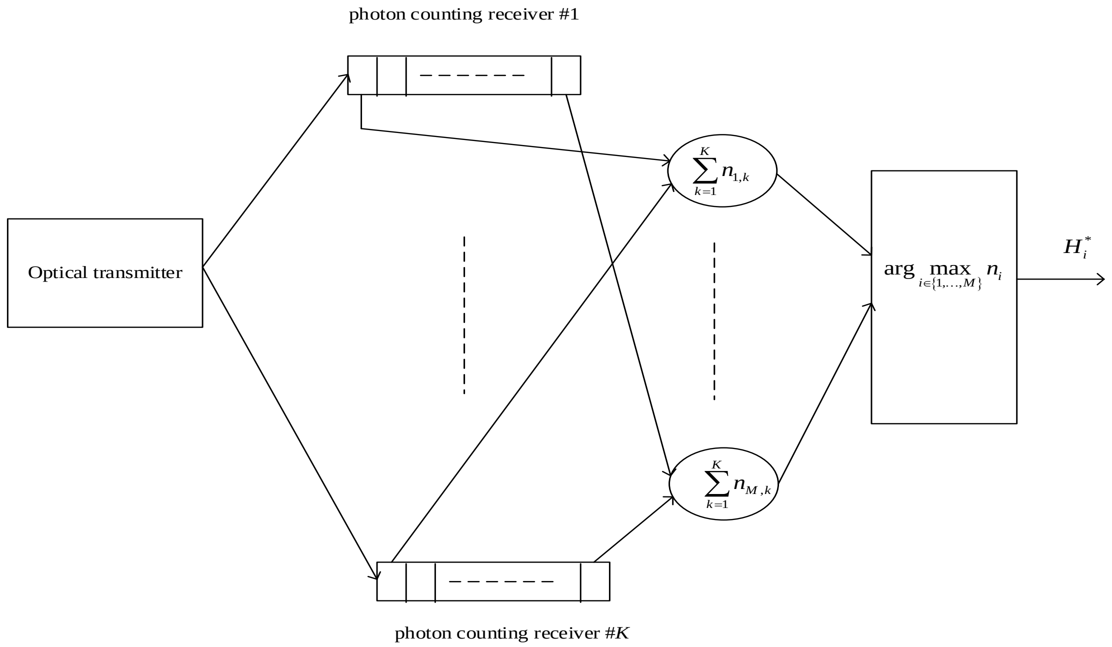

Fig. 2. Scheme 2: Chip-level processing by data fusion

A. Symbol-level processing by decision fusion

The common receiver exploits majority voting rule, in which it decides $H_i; i=1,\ldots,M$ if and only if the number of local receivers that decides $H_i; i=1,\ldots,M$ is the largest. Let the number of detected photons at the *i*th chip of the *k*th local photon counting receiver be denoted by $n_{i,k}; i=1,2\ldots,M,\quad k=1,\ldots,K$, each photon counting receiver first performs its own local detection by

$$H_{i,k}^{*} = \arg\max_{i\in\{1,\ldots,M\}} n_{i,k}; k=1,\ldots,K \tag{11}$$

We assume that the number of local photon counting receivers, *K*, is odd. Therefore, the common receiver decides H_i provided that there are at least $\frac{K+1}{2}$ local receivers decide H_i. We may separate the local users into two set, in which $C_1=\{1,\quad 2,\quad \cdots \quad k\}$ be the users set that make correct decision and $C_2=\{k+1,\quad k+2,\quad \cdots \quad K\}$ be the users set that make erroneous decision. According to the majority rule, the overall correct detection probability at the common receiver can be obtained as

$$P_{C,1} > \sum_{x=\frac{K+1}{2}}^{K} \left\{ \begin{array}{l} \binom{K}{x} \underbrace{P_i(C)\times\cdots\times P_j(C)}_{\text{total } x \text{ terms chosen from the set } C_1} \\ \times \underbrace{\left(1-P_m(C)\right)\times\cdots\times\left(1-P_n(C)\right)}_{\text{total } (K\text{-}x) \text{ terms chosen from the set } C_2} \end{array} \right\} \tag{12}$$

Please note that in writing (12), we have neglected the case that although less than $\frac{K+1}{2}$ local users make correct decision, nevertheless, the transmitted symbol is still corrected detected by the majority rule. Specifically, if $K_{s,1}=K_{s,2}=\cdots=K_{s,K}=K_s$, (12) can be simplified as

$$P_{C,1} > \sum_{x=\frac{K+1}{2}}^{K} \binom{K}{x} \left(P(C)\right)^{x} \left(1-P(C)\right)^{K-x} \tag{13}$$

where $P(C)$ is as derived in (9). And the overall SER is upper-bounded by

$$P_{s,1} = 1-P_{C,1} < \sum_{x=\frac{K+1}{2}}^{K} \binom{K}{x} \left(P(C)\right)^{x} \left(1-P(C)\right)^{K-x} \tag{14}$$

B. Chip-level processing by data fusion

Instead of transmitting the local decision to the common receiver, the data fusion scheme regards all the local users as a joint receiver. Each local photon counting receiver first sends the observed value directly to the common receiver, in which new decision statistic is formed by summing the observed value at each chip received from all local photon counting receivers. The observed value at the *i*th chip of the common receiver yields

$$n_i = \sum_{k=1}^{K} n_{i,k}; i=1,2,\ldots,M \tag{15}$$

We may regard the common receiver as a new and joint photon counting receiver. There then, the ML decision rule as depicted in (4) can be applied

$$H_i^{*} = \arg\max_{i\in\{1,\ldots,M\}} n_i$$

To proceed, we first visit the theory of Poisson random variable [8]:

If $\{X_i\}_{i=1,2,\ldots,n}$ *are independent Poisson random variables with parameters* $\{\lambda_i\}_{i=1,2,\ldots,n}$, *respectively, then the sum* $X=\sum_{i=1}^{n} X_i$ *is still Poisson distribution with parameters* $\Lambda=\sum_{i=1}^{n}\lambda_i$.

If the *i*th chip is only background radiation, then based on (14) and the above characteristic of Poisson random variable, we have $n_i \sim Po(KK_b)$. Hence, the probability that there are *n* detected photons is

$$P(n_i=n) = \frac{(KK_b)^n}{n!} e^{-KK_b}; n=0,1,2,\ldots \tag{16}$$

Alternatively, if a laser pulse is transmitted at the ith chip, then $n_i \sim Po\left(\sum_{k=1}^{K} K_{s,k} + KK_b\right)$. Thereby, the probability that there are n photons becomes

$$P(n_i = n) = \frac{\left(\sum_{k=1}^{K} K_{s,k} + KK_b\right)^n}{n!} e^{-\left(\sum_{k=1}^{K} K_{s,k} + KK_b\right)}; n = 0,1,2,\ldots \quad (17)$$

Substituting (17), (16) into (9), after some manipulations, we arrive at the correct detection probability by chip-level processing

$$P_{C,2} = e^{-\left(\sum_{k=1}^{K} K_{s,k} + MKK_b\right)} \times \left\{ \frac{1}{M} + \sum_{n_1=1}^{\infty} \frac{\left(\sum_{k=1}^{K} K_{s,k} + KK_b\right)^{n_1}}{n_1!} \times \left[\sum_{l=0}^{M-1} \frac{1}{l+1} \binom{M-1}{l} \left(\frac{(KK_b)^{n_1}}{n_1!} \right)^l \left(\sum_{j=0}^{n_1-1} \frac{(KK_b)^j}{j!} \right)^{M-1-l} \right] \right\} \quad (18)$$

And the overall SER is

$$P_{s,2} = 1 - P_{C,2} \quad (19)$$

IV. Performance Evaluation

In this section, we aim at evaluating system performance of the proposed two diversity schemes through computer simulations. Without loss of generality, we assume that $K_{s,1} = K_{s,2} = \cdots = K_{s,K} = K_s$ for all the simulation examples. Fig. 3 presents SER of *M-ary* PPM for different values of M, where we set K_b=0.5, K_s=3, and the number of photon counting receivers is 7. As we increase M from 2 (BPPM) to 32, SER increases gradually as well. This is as expected since higher-order modulation (as M is large) achieves bandwidth efficiency at the expense of higher SER. Moreover, we can observe from the result that scheme 2 outperforms scheme 1. Indeed, the data fusion and decision fusion has an analogy to the soft decision and hard decision, respectively, in communication system.

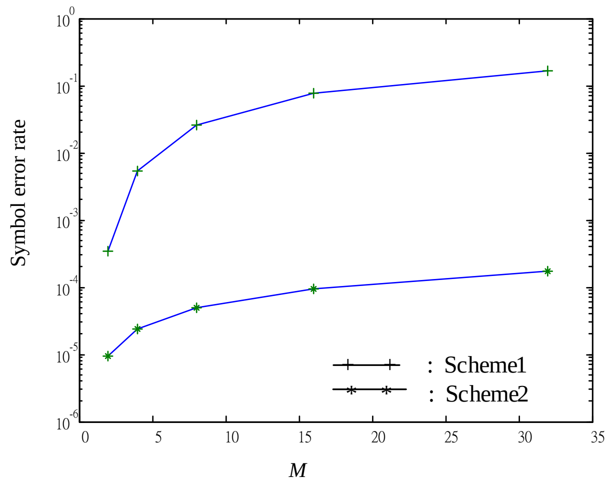

Fig. 3. Symbol error rate (SER) of *M-ary* PPM for different values of *M*.

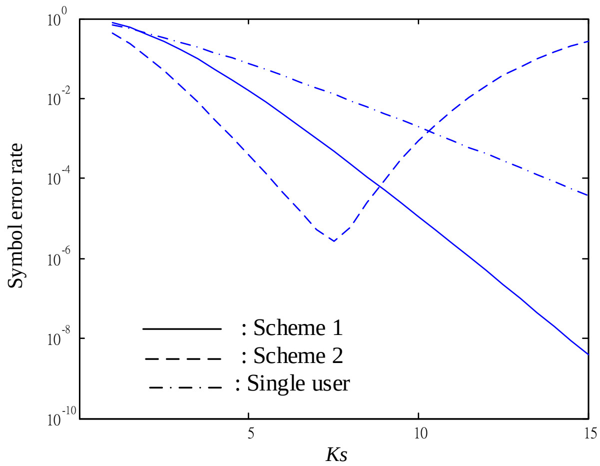

Fig. 4. SER with respect to K_s.

Fig. 4 presents SER with respect to K_s, where 8PPM is employed and K_b is set to be 0.5. The performances for scheme 1 and scheme 2 (in both schemes, K=3) and the case for single photon counting receiver (K=1) are provided for comparison. As we can observe from the simulation result, the SER performance of both the single user case (without cooperation) and scheme 1 improve as K_s increases, since K_s corresponds to the average energy of laser pulse. Moreover, scheme 1 outperforms single user case since receive diversity has been employed (in this simulation example, the diversity order is K=3). Specifically, though scheme 2 outperforms scheme 1 in the low K_s region, nevertheless, SER of scheme 2 increases rapidly as K_s exceeds 7.5. While in the high K_s region (K_s>9), the performance of scheme 2 becomes worse than scheme 1 and is even worse than the case of single photon counting receiver when K_s>12. The reason that the SER curve of scheme 2 decreases to a minimum and then increases in high K_s region arises from the Poisson channel model:

As we have derived in section III.2, the detected photons of scheme 1 and scheme 2 at the time slot that laser pulse is present (signal slot) is $n_i \sim Po(K_s + K_b)$ and $n_i \sim Po(KK_s + KK_b)$, respectively. Hence, as K_s is large, variance of scheme 2 is much greater than that of scheme 1. Therefore, the SER performance of scheme 2 is worse than scheme 1 and even the conventional single photon counting receiver in high K_s region.

Fig. 5 presents SER with respect to the number of photon counting receivers, where we set *M*=4, K_b=0.2 and K_s=2. As revealed in Fig. 5, SER performance improves as we increase *K* (the diversity order). However, as *K*>11, the performance of scheme 2 degrades severely. When *K* exceeds 15, the performance of scheme 2 becomes inferior to scheme 1. This is due to the fact that we have derived in section III.2, the detected photons at the signal slot and the noise slot of scheme 2 is $n_i \sim Po(KK_s + KK_b)$ and $n_i \sim Po(KK_b)$, respectively. Hence, as *K* is large, variances of scheme 2 in both signal and noise time slots increase dramatically. Consequently, the SER performance of scheme 2 degrades severely and becomes worse than scheme 1 in large *K* scenario.

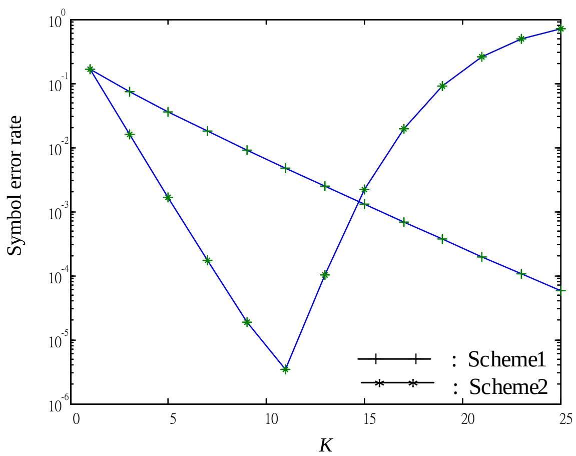

Fig. 5. SER with respect to the number of local photon counting receivers.

V. Conclusions

In this paper, we have developed two receive diversity schemes for NLOS optical wireless scattering channel with multiple photon counting receivers. We have derived the symbol error probability for both schemes based on *M-ary* PPM and Poisson channel model. Both theoretical analysis and computer simulation results show significant performance gain brought by the multiple receivers. The results demonstrated that using receive diversity, SER has substantially decreased compared to the case without diversity. Specifically, scheme 2 outperforms scheme 1 in general case, nevertheless, it was also verified that scheme 1 is superior to scheme 2 in the scenario of large *K* and/or K_s. Therefore, the results suggest as a candidate in practical wireless optical system design.

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收件：**108.08.30**　修正：**108.10.17**　接受：**108.11.06**