Space Division and Time Division Multiple Access System based on Intensity Distribution for Hybrid-LOS Indoor Optical Wireless Communication

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Abstract
This paper proposes a novel signal discrimination scheme for spatially multiplexed optical signals using a spatial intensity distribution detection technique and applies it to a space division multiple access (SDMA) in hybrid line-of-sight (hybrid-LOS) indoor optical wireless communication system. In the proposed scheme, multiple terminals simultaneously transmit their optical signals to access point (AP) using on-off-keying (OOK) modulation, and the combined optical signals are received by a photodetectors array (PD-array), where multiple PDs are disposed to observe the spatial intensity distribution of received signals. Because its spatial intensity distribution is subject to the signals transmitted from individual terminals, AP can identify the transmitted data by determining the transmitted spatial intensity distribution. In order to ensure a required discriminability of the transmitted intensity distributions, the proposed signal discrimination scheme is further applied to a space division and time division multiple access (SD/TDMA), and a scheduling algorithm is employed in which terminals with high discriminatory of the intensity distributions are allocated to the same time slot. Numerical results show that SD/TDMA using the proposed signal discrimination scheme increases the system throughput and the number of terminals that can access to the AP.

1. Introduction
The emergence of many kinds of information terminals in work and living environments is accelerating the introduction of high-speed indoor wireless communication system. Indoor optical wireless communication system is one of the possible ways to establish high-speed wireless connection and has advantages over radio systems such as light source and photodetector (PD) capable of high-speed operation with low cost, wireless transmission using unregulated bandwidth, immune to radio interference and so on [1]-[5].

Among several configurations of optical wireless communication systems, at present, most optical wireless communication systems are of a directed line-of-sight (directed-LOS) system or a hybrid LOS (hybrid-LOS) system because both systems are relatively free from multipath distortion and achieve high transmission rates. The directed-LOS system fully exploiting a potential for high-speed transmission is well suited for point-to-point communication system, but is not suited for multiple access system since the LOS path is always occupied with one transmitter and receiver pair and directional controls of both the transmitter and the receiver are required. On the other hand, the hybrid-LOS system shown in Fig.1 allows multiple terminals to communicate with an access point (AP) by introducing multiple access technique.

Although several kinds of multiple access techniques including time division multiple access (TDMA) [6], code division multiple access (CDMA) [7], and carrier sense multiple access (CSMA) [8] can be applied to the hybrid-LOS system, these multiple access techniques decrease the transmission rates of each terminal. Moreover, in optical wireless communications, the most viable modulation is an intensity modulation (IM) and it is not practical to perform a homodyne or a heterodyne detection of the received signal. This means that the multiple access technique in which multiplexed signals are discriminated by coherent detection cannot be applied to the indoor optical wireless communication system, and the transmission rate of each terminal is decreased. Since the feature of high-speed transmission is a strong advantage of the optical wireless communication system, it is necessary to introduce the multiple access technique without decreasing the transmission rates of each terminal.

As the multiple access technique utilizing a propaga-
tion characteristics of optical wireless signal, spatial division multiple access (SDMA) has been considered [9] [10]. SDMA provides spatially divided multiple channels using angle-diversity receiver equipped with multiple PDs and enables the terminals to access the AP without requiring a loss of transmission rates of each terminal. In a conventional SDMA for hybrid-LOS system, the angle-diversity receiver has a discriminability for the optical signals transmitted from different directions. Therefore, the number of terminals that can simultaneously access to the AP is strictly limited and the multiple terminals placed in the same spatially divided channel cannot access to the AP. To enhance the capability of SDMA for hybrid-LOS system, it is necessary to explore the discrimination scheme for spatially multiplexed optical signal.

This paper proposes a novel signal discrimination scheme for the spatially multiplexed optical signals and applies it to the SDMA for hybrid-LOS indoor optical wireless communication system. In the proposed scheme, multiple terminals simultaneously transmit their optical signals to access point (AP) using on-off-keying (OOK) modulation, and the combined optical signals are received by a photodetectors array (PD-array), where multiple PDs are disposed to observe the spatial intensity distribution of optical signals. Because the terminals transmit their data using OOK modulation, the spatial intensity distribution observed by the AP is subject to the data transmitted from the terminals, and the AP can identify the terminals transmitting the optical signal by determining the transmitted intensity distribution. Of course, the transmitted intensity distributions are not orthogonal and the discriminability of transmitted intensity distributions is much related to differences of intensity distributions. This implies that the number of terminals that can access to the AP will be limited depending on the number and positions of the terminals. In order to enhance the discriminability of the transmitted intensity distributions, the proposed signal discrimination scheme is further applied to a space division and time division multiple access (SD/TDMA). In the SD/TDMA, the number of terminals simultaneously access to the AP is reduced and the discriminability required to enable SDMA is ensured by introducing a scheduling algorithm in which terminals with higher discriminatory of transmitted intensity distributions are allocated to the same time slot.

The reminder of this paper is organized as follows. Section 2 describes the principle of the proposed discrimination scheme for spatially multiplexed OOK signals. In section 3, performances of SDMA are evaluated and the capability of SDMA using proposed signal discrimination scheme is discussed. In section 4, the proposed signal discrimination scheme is applied to the SD/TDMA and the throughput performance of SD/TDMA is evaluated. Finally, section 5 concludes our discussions.

2. SDMA using Proposed Signal Discrimination Scheme

2.1 Principle of Proposed Signal Discrimination Scheme

In the uplink of hybrid-LOS system, even though the terminal transmits an optical signal to the AP using a narrow beam light source, the transmitted optical signal is spatially spread before arriving at the AP. This means that the transmitted signal has the spatial intensity distribution and its shape is different according to the position of the terminal. If plural terminals simultaneously transmit their optical signals, the intensity distribution becomes a superposition of the individual distributions constructed by each transmitted signal. In addition, when the terminals transmit their signals using OOK-IM/DD (Intensity Modulation / Direct Detection) scheme, the spatial intensity distribution is subject to the data transmitted from the terminals. Therefore, if the AP observes the intensity distribution of the received signal and determines the transmitted spatial intensity distribution, the AP can identify the data transmitted from the individual terminals.

Based on the principle described above, this paper proposes a novel signal discrimination scheme for spatially multiplexed signals using a spatial intensity distribution detection technique and applies it to the SDMA. In the proposed scheme, each terminal transmits the signals to the AP using OOK modulation, and the transmitted signal is received by the AP equipped with PD-array.
Here, we evaluate the spatial intensity distribution observed by the PD-array and discuss the potential of the proposed signal discrimination scheme. Figure 2 shows the alignment of PDs on the PD-array, and Tab.1 shows the parameters of the hybrid-LOS system employed in this evaluation. As shown in Fig.1, the AP is placed on the center of the ceiling, and the terminals exist on the floor. In addition, as shown in Fig.2, the size of the receiver is $x \times x \text{cm}$, and $N_{\text{PD}}$ PDs are placed on the PD-array.

Figure 3 (a) and (b) show the intensity distributions observed by the PD-array. In each figure, we assume that the number of PDs on the PD-array is 15 × 15 and only one terminal exists on the point shown in red. In Fig.3 (a) and (b), the spatial intensity distributions have quite different shapes according to the positions of terminals. From this result, we can confirm the possibility of SDMA scheme using intensity distribution detection technique.

Of course, in the proposed signal discrimination scheme, because the optical signal is transmitted using IM/DD scheme and the orthogonality of the multiplexed signals is not guaranteed, the maximum number of terminals that can simultaneously access to the AP will be limited. In addition, we can expect that, even in the case of the small number of terminals, when plural terminals exist on the same place on the floor, some intensity distributions have the same shape and these terminals cannot simultaneously access to the AP. Capability of SDMA using proposed signal discrimination scheme will be discussed in Section 3.

### 2.2 Decision of Transmitted Spatial Intensity Distribution

In the SDMA using proposed signal discrimination scheme, the AP can decide the transmitted data by determining the transmitted spatial intensity distribution. When $N_{\text{ter}}$ terminals simultaneously transmit their data using OOK modulation, $2^{N_{\text{ter}}}$ kinds of intensity distributions can be observed at the AP. Among these $2^{N_{\text{ter}}}$ kinds of intensity distributions, the AP determines the transmitted one by observing the received intensity distribution. In this paper, as a method to determine the transmitted intensity distribution, a maximum likelihood (ML) detection scheme is employed.

Outputs of the signal and the noise components of the $N_{\text{PD}}$ PDs for the $k$-th ($1 \leq k \leq 2^{N_{\text{ter}}}$) candidate intensity distribution is expressed as

$$S_k = [s_{k,1}, \ldots, s_{k,m}, \ldots, s_{k,N_{\text{PD}}}],$$

$$N_k = [n_{k,1}, \ldots, n_{k,m}, \ldots, n_{k,N_{\text{PD}}}],$$

where $s_{k,m}$ and $n_{k,m}$ ($1 \leq k \leq 2^{N_{\text{ter}}}, 1 \leq m \leq N_{\text{PD}}$) are the outputs of the signal and noise components of the $m$-th PD, respectively. Using Eqns.(1) and (2), the outputs of $N_{\text{PD}}$ PDs for the $k$-th ($1 \leq k \leq 2^{N_{\text{ter}}}$) candidate intensity distribution is expressed as

$$R = [r_1, \ldots, r_m, \ldots, r_{N_{\text{PD}}}],$$

where $r_m$ ($1 \leq m \leq N_{\text{PD}}$) is the output of the $m$-th PD and it is given by

$$r_m = s_{k,m} + n_{k,m}. \tag{4}$$

Table 1 Parameters of the hybrid-LOS system employed in performance evaluation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of Room</td>
<td>$10 \text{ m} \times 10 \text{ m} \times 3 \text{ m}$</td>
</tr>
<tr>
<td>Transmission Rate $B$</td>
<td>1 Gbps</td>
</tr>
<tr>
<td>Half-power Angle of Light Source $\theta_{1/2}$</td>
<td>0.8 deg</td>
</tr>
<tr>
<td>FOV of Photodetector $\Psi_k$</td>
<td>74.2 deg</td>
</tr>
<tr>
<td>Power of Ambient Light Interference $P_b$</td>
<td>-30 dBm</td>
</tr>
<tr>
<td>Size of Receiver $L_{rx}$</td>
<td>10 cm</td>
</tr>
<tr>
<td>Area of Photodetector $A$</td>
<td>$\pi L_{rx}^2 / 4N_{\text{PD}} \ \text{cm}^2$</td>
</tr>
<tr>
<td>Required Communication Quality</td>
<td>BER $\leq 10^{-6}$</td>
</tr>
</tbody>
</table>

Figure 3 Examples of the intensity distributions observed by the PD-array.
Prob \( P(R | S_i) = \prod_{m=1}^{N_{eq}} p(r_m - s_{k,m}) \). \( (5) \)

In addition, suppose \( n_{k,m} \) is additive white Gaussian noise with power \( \sigma^2_{k,m} (1 \leq k \leq 2^{N_{ae}}, 1 \leq m \leq N_{PD}) \), Eqn.(5) can be expressed as \[11\]

\[ \text{Prob} \{ R | S_i \} = \prod_{m=1}^{N_{eq}} \frac{1}{\sqrt{2\pi\sigma^2_{k,m}}} \exp \left( -\frac{(r_m - s_{k,m})^2}{2\sigma^2_{k,m}} \right). \] \( (6) \)

The intensity distribution \( S_i \) that maximizes Eqn.(6) also maximizes the log-likelihood function given by

\[ \Lambda_k = -\sum_{m=1}^{N_{eq}} \left( \frac{1}{2} \log \sigma^2_{k,m} + \frac{(r_m - s_{k,m})^2}{2\sigma^2_{k,m}} \right). \] \( (7) \)

In the proposed SDMA scheme, using the \( 2^{N_{ae}} \) kinds of the reference intensity distributions given in Eqn.(1) and the received spatial intensity distribution given in Eqn.(3), the AP determines the intensity distribution \( S_i \) that maximizes Eqn.(7) as the transmitted one.

### 2.3 Discriminability of Intensity Distributions

As expected from the principle of signal discrimination scheme shown above, the discriminability of the transmitted intensity distributions are important factor to dominate the capability of SDMA. In this subsection, as a measure for the capability of the proposed SDMA scheme, we introduce a function \( \text{Diff}(S_a, S_b) \) \( (1 \leq a, b \leq 2^{N_{ae}}, a \neq b) \) which is defined as

\[ \text{Diff}(S_a, S_b) = \sum_{i=1}^{N_{eq}} \left| s_{a,i} - s_{b,i} \right|. \] \( (8) \)

\( \text{Diff}(S_a, S_b) \) given as Eqn.(8) represents the difference of two candidate intensity distributions \( S_a \) and \( S_b \). If the \( \text{Diff}(S_a, S_b) \) becomes large for the given intensity distributions \( S_a \) and \( S_b \), these two intensity distributions are quite different, and the transmitted intensity distribution will be determined without error. On the other hand, if the function \( \text{Diff}(S_a, S_b) \) is too small, these two intensity distributions are almost the same, and it will be difficult to determine the transmitted intensity distribution without error. When \( N_{iter} \) terminals simultaneously access to the AP, the number of functions \( \text{Diff}(S_a, S_b) \) \( (1 \leq a, b \leq 2^{N_{ae}}, a \neq b) \) given by Eqn.(7) becomes \( 2^{N_{ae}} \cdot C_2 \). However, two intensity distributions having a minimum value of \( \text{Diff}(S_a, S_b) \) are most similar to each other, and the decision errors between these two distributions dominate the capability of SDMA using proposed signal discrimination scheme. Therefore, as the measure for the capability of SDMA scheme, we employ the minimum value among \( 2^{N_{ae}} \cdot C_2 \) kinds of \( \text{Diff}(S_a, S_b) \) and it is expressed as

\[ D_{min} = \min_{a \neq b} \left[ \text{Diff}(S_a, S_b) \right]. \]

\[ = \min_{a \neq b} \left[ \sum_{i=1}^{N_{eq}} \left| s_{a,i} - s_{b,i} \right| \right]. \] \( (9) \)

### 3. Performance of SDMA using Proposed Signal Discrimination Scheme

Performances of SDMA using proposed signal discrimination scheme are evaluated in this section. As discussed in the previous section, the discriminability of the transmitted intensity distributions dominates the capability of the proposed SDMA scheme and it depends on the minimum difference of intensity distributions \( D_{min} \). As the number of terminals increases, the minimum difference \( D_{min} \) becomes small and the maximum number of terminals that can simultaneously access to the AP is limited. Moreover, even in the case of the small number of terminals, when plural terminals exist on the same place on the floor, some intensity distributions have the same shape and these terminals cannot access to the AP.

Here, as one of the countermeasures to enhance the discriminability of the transmitted intensity distributions, directions of terminals are controlled so as to aim at the different points on the PD-array. Figure 4 illustrates the aimed points on the PD-array. As shown in this figure, the directions of terminals are controlled so as to aim at one of the four aimed points and the distance between the adjacent aimed points is \( L_{sp} \) cm. Note that, in the case of the distance \( L_{sp} = 0 \) cm, the directions of all terminals are controlled so as to aim at the same point on the PD-array.

Figure 5 shows the average number of terminals that can simultaneously access to the AP \( N_{correct} \) versus the dis-
tance between adjacent point $L_{sp}$. In this figure, the average number of terminals $N_{correct}$ can be increased for the case of $4 \leq L_{sp} \leq 8$ cm. This is because, for the case of smaller $L_{sp}$, the distance between the adjacent aimed points is too small, and the minimum difference of the candidate intensity distributions is decreased. In addition, for the case of larger $L_{sp}$, since the directions of all terminals are controlled so as to aim at the outside of PD-array, the received signal power and the minimum difference of the candidate intensity distributions are decreased. The decrease in the differences of intensity distributions reduces the discriminability of the transmitted intensity distributions, and the average number of terminals that can simultaneously access to the AP is limited.

In order to investigate the capability of SDMA using proposed signal discrimination scheme more in detail, Fig.6 shows the average number of terminals that can simultaneously access to the AP ($N_{correct}$) and the number of terminals existing in the coverage of AP ($N_{ter}$). In this figure, when the distance between adjacent aimed points $L_{sp} = 0$ cm and 10 cm, $N_{correct}$ is smaller than $N_{ter}$ for the case that $N_{ter} \geq 2$. This means that, in the case of $L_{sp} = 0$ cm and 10 cm, when plural terminals exist in the coverage of AP, all of terminals cannot always access to the AP. On the contrary, when the distance $L_{sp} = 6$ cm, $N_{correct}$ equals to $N_{ter}$ until $N_{ter} \leq 4$, and all of terminals can simultaneously access to the AP. However, even in the case of $L_{sp} = 6$ cm, if more than 5 terminals exist in the coverage of AP, all of terminals cannot simultaneously access to the AP.

In this section, as the countermeasure to enhance the discriminability of the transmitted intensity distributions, the directions of terminals are controlled so as to aim at the different points on the PD-array. In the following section, as one of the alternatives to enhance the discriminability of the intensity distributions, the proposed signal discrimination scheme is further applied to the SD/TDMA, and a scheduling algorithm to ensure a required discriminability is introduced.

4. SD/TDMA using Proposed Signal Discrimination Scheme

4.1 Principle of Proposed SD/TDMA Scheme

As shown in the previous section, as the number of terminals existing in the coverage of AP increases, the discriminability of the transmitted intensity distributions is reduced, and the number of terminals that can simultaneously access to the AP using SDMA is limited. In addition, even in the case of the small number of terminals, when plural terminals exist on the same place, these terminals cannot simultaneously access to the AP. In this section, to enhance the discriminability of the transmitted intensity distributions, the proposed signal discrimination scheme is further applied to the SD/TDMA.

In the SD/TDMA using proposed signal discrimination scheme, terminals transmit their optical signals in the assigned time slot, and the orthogonalities among intensity distributions transmitted in different time slots can be guaranteed. The terminals transmitting their optical signal in the same time slot simultaneously access to the AP using SDMA shown in the previous section. Because the number of terminals simultaneously access to the AP is reduced by introducing TDMA, the discriminability of the transmitted intensity distribution will be enhanced. More-
over, the discriminability required to enable SDMA is ensured by introducing a scheduling algorithm in which terminals with higher discriminatory of transmitted intensity distributions are allocated to the same time slot. Compared to the SDMA discussed in the previous section, a throughput performance of each terminal is degraded because the optical wireless channel is divided to multiple time slots. However, the number of terminals that can access to the AP can be increased by introducing the SD/TDMA. In addition, compared to a conventional TDMA, the throughput performance of each terminal will be much improved, because multiple terminals share the same time slot by using SDMA.

Figure 7 shows a medium access control (MAC) layer protocol in a preprocessing process for SD/TDMA using proposed signal discrimination scheme. Figure 8 illustrates the examples of frame structures for the SD/TDMA using proposed signal discrimination scheme and the conventional TDMA.

In the protocol shown in Fig. 7, at first, a beacon (BEA) signal is transmitted from the AP to each terminal to acknowledge the number of terminals existing in the coverage of AP. BEA signal includes a timer for the time synchronization and a transmission interval of BEA signal. Next, the terminals which received the BEA signal reply a request for pilot (RFP) signals to inform their own existence to the AP according to a carrier sense multiple access with collision avoidance (CSMA/CA) protocol. After receiving the RFP signal from each terminal, in order to inform a receipt of RFP signal, the AP transmits an acknowledgement (ACK) signal to each terminal. If the AP does not receive any RFP signals in the duration of $\text{DIFS} + \text{CW}_{\text{max}} \times (\text{Back-off Slot Time})$ after sending the ACK signal, the AP transmits a schedule of pilot (SOP) signal in order to complete the random access based on CSMA/CA protocol and inform a schedule for a transmission of a pilot (PIL) signal. Each terminal transmits a PIL signal according to the time schedule denoted in the SOP signal. Using the PIL signals transmitted from the terminals, the AP generates the reference intensity distributions $S_k (1 \leq k \leq 2^{N_{\text{ter}}})$ given in Eqn.(1) and decides the time slot assignment according to the scheduling algorithm. Finally, the AP transmits a permission of data (POD) signal which informs a start of the transmission of data packet.
In order to fully exploit the capability of SD/TDMA using proposed signal discrimination scheme, the terminals existing in the coverage of AP are necessary to be assigned in time slots so as to ensure the required discriminability of the intensity distributions in all time slots. In this paper, as a measure of the required discriminability of the intensity distributions, we employ $D_{\text{min}}$ given in Eqn. (9). In addition, from the numerical results for the performance of SDMA using proposed signal discrimination scheme, we assume that $D_{\text{min}} \geq 10^{-1}$ mA (bit error rate $\leq 10^{-6}$) is required to enable simultaneously transmissions of optical signals using SDMA. The scheduling algorithm for proposed SD/TDMA scheme is shown in Fig. 9.

4.2 Performance of SD/TDMA using Proposed Signal Discrimination Scheme

Throughput performances of SD/TDMA using proposed signal discrimination scheme is evaluated. Table 2 shows the parameters employed in this performance evaluation. In the performance evaluation, we assume that the RFP signals can be transmitted without collision. Under this assumption, the average of random back-off time in the preprocessing process is obtained by

$$T_{\text{Back Off}} = CW_{\text{min}} \times \text{Back off Slot Time}/2. \quad (10)$$

Figure 10 shows the system throughput performances of SD/TDMA using proposed signal discrimination scheme for the cases that $L_{\text{sp}} = 0$ cm, 6 cm, and 10 cm, respectively. For comparison, the system throughput performance of conventional TDMA is also shown in this figure. In the performance evaluation, the system throughput is defined as the sum of throughputs of all terminals existing in the coverage of the AP.

In Fig. 10, the system throughput performances of SD/TDMA are much higher than that of conventional TDMA. Moreover, in the case of SD/TDMA, the system throughputs are increased as the number of terminals increases. In conventional TDMA scheme, each time slot is occupied only one terminal, and the system throughput is constant regardless of the number of terminals. On the contrary, in the SD/TDMA using proposed signal discrimination scheme, multiple terminals share the same time slot and simultaneously transmit their optical signals to the AP by SDMA. Therefore, the system throughput of SD/TDMA is much higher than that of conventional TDMA. From this result, we can conclude that the SD/TDMA using proposed signal discrimination scheme is effective as the multiple access technique for hybrid-LOS indoor optical wireless communication system.

5. Conclusions

In this paper, we proposed the novel signal discrimination scheme for spatially multiplexed signals using a spatial intensity distribution detection technique and applied it to the SDMA for hybrid-LOS indoor optical wireless communication system. Numerical results showed that the discriminability of the transmitted intensity distributions dominates the potential of SDMA using proposed
signal discrimination scheme, and it much depends on the differences between candidate intensity distributions. In order to ensure the required discriminability of the transmitted intensity distributions, the proposed signal discrimination scheme was further applied to the SD/TDMA, and the scheduling algorithm was introduced in which the terminals with high discriminatory of the intensity distributions are allocated to the same time slot. Numerical results confirmed that the system throughput of SD/TDMA using proposed signal discrimination scheme is much higher than that of conventional TDMA.

References