Simplified calculation method of indoor optical impulse response based on recursive algorithm

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***Abstract*—A simplified method for the calculation of indoor wireless optical impulse response based on classical recursive algorithm is demonstrated. In the proposed algorithm, the optical characteristics of emitting and receiving elements have been used to reduce the complexity of computations while no sacrifice of accuracy is introduced. Theoretical investigation shows that the elementary computations for the third reflection decreases by nearly 50% in comparison with the one that utilizes the classical recursive algorithm, and can obtain a higher reduction percentage when more reflections are to be concerned.**

Keywords: impulse response; recursive algorithm; optical wireless

I. INTRODUCTION

It has been widely accepted that the next generation of wireless communication system will be a mixture of several technologies. Along with the progress made in LED devices, indoor optical wireless communications [1] either visible light communication (VLC) [2,3] or infrared communication (IR) have gained increasing interests in recent days [4]. However, the existence of the multiple reflections which introduces ISI (intersymbol interference) is a challenge for high speed communications. In order to examine the reflection effect on the communication system, several methods and characteristics of channels have been proposed to evaluate the impulse response. The issues that should be taken into account are as follows. First, as far as the room environments are concerned, the model is represented by empty room or furnitured room. Since the computation of impulse response of VLC is hundreds or even thousands times of the IR case, the investigation of the VLC channel is often limited to ideal empty rooms [5,6]. Fortunately, after over a decade of research in IR field, the IR impulse response has been explored in comparatively complexity which enables the influence of different furniture, people and shadow [7-9]. Second, the reflector are modeled as the ideal Lambertian reflectors [10] or the sum of diffusive and specular reflectors [11]. Third, classical recursive method[12] together with Monte Carlo ray tracing approach [13,14] are two common algorithms to simulate impulse response. Monte Carlo ray tracing algorithm reduces the elementary computations to be linear with reflection times, whereas it brings error since its random generation of rays [15,16]. Aiming to alleviate random error, several researches [5,17,18] on channel impulse response has been evaluated by classical recursive algorithm whose effectiveness has been demonstrated by experimental results [19]. However, the elementary computations increase exponentially with times of reflection, which restrict the simulated impulse response being in lower reflection orders.

In this work, we propose a simplified calculation method based on recursive algorithm that excludes some of the redundant terms in computation while contains the same accuracy with the classical algorithm. The method is established in an empty room with ideal reflectors. Theoretical analysis shows that the saved elementary computation for the third reflection is nearly 50%. Simulation results of the proposed algorithm are in agreement with the classical algorithm. In the next section, the models of optical wireless channels and the classical recursive algorithm are introduced. Then, we

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demonstrated the modified algorithm and its simulation result in Section III and IV respectively.

II. CLASSICAL RECURSIVE ALGORITHM

A. Models of Source and receiver

The LED source can be modeled as a Lambertian radiation $R(\phi)$:

$$R(\phi) = \frac{n+1}{2\pi} P_S \cos^n(\phi) \tag{1}$$

where $R(\phi)$ is the radiation intensity, n is the mode number of LED source, P_S is the power of the source, and ϕ corresponds to the emitting directivity away from the normal of the source. A point source can be denoted by:

$$S = \{r_S, \hat{n}_S, n\} \tag{2}$$

where r_S is its position, and $\hat{n}_S$ is its orientation~~,~~

A receiver can be expressed by:

$$R = \{r_R, \hat{n}_R, A_R, FOV\} \tag{3}$$

where FOV is the field of view for the receiver, r_R is its position, $\hat{n}_R$ is its orientation, A_R is its area.

B. The classical recursive algorithm

The total impulse response is the sum of individual impulse response:

$$h(t;S,R) = \sum_{K=0}^{\infty} h^{(k)}(t;S,R) \tag{4}$$

The recursive algorithm is given by:

$$h^{(k)}(t;S,R) = \frac{n+1}{2\pi}\int_S \frac{\rho_r \cos^n(\phi)\cos\cos(\phi)}{R^2} \tag{5}$$

$$rect(2\theta/\pi)h^{(k-1)}(t-R/c;\{r,\hat{n},1\},\mathrm{R})dr^2$$

where $\hat{n}$ and ρ_r are the normal and reflectivity at position r, respectively. R is the distance between the secondary source reflector and secondary receiver. θ denotes the angle between R and normal of secondary receiver. Eq.(5) is performed with respect to r which is on the surface of secondary source S of all reflectors. If the surfaces of reflectors are divided into N individual ΔA, Eq. (5) can be calculated numerically by:

$$h^{(k)}(t;S,R) \approx \frac{n+1}{2\pi}\sum_{i=1}^{N} \frac{\rho_i \cos^n(\phi)\cos\cos(\theta)}{R^2} \tag{6}$$

$$rect(2\theta/\pi)h^{(k-1)}(t-R/c;\{r,\hat{n},1\},\mathrm{R})\Delta A$$

where N is the total number of elements, and ΔA is the area.

III. THE SIMPLIFIED ALGORITHM

A. The simplified algorithm

In the classical recursive algorithm, each element receives optical power from every secondary reflector including the ones from the same surface with the receiving element. In fact, one can simplify the calculation by investigating the Lambertian characteristic of both the LED source and secondary reflectors. Considering the nature of emitting source, as specified in (1), the radiation intensity decreases with respect to the increase of angle ϕ between the surface normal and observer, until it drops to 0 when the angle $\phi = \pi/2$. So the parts can be eliminated for calculating the power from those reflectors which are on the same surface of the receiving elements ($\phi > \pi/2$).

In the simplified algorithm, all the elements are separated into 6 groups within which elements are on the same surface and each group of elements only receives reflecting energy from the rest groups of elements (i.e., $0 < \phi < \pi/2$), as depicted in Figure 1(a).The symbols of *Si*, *Ni*, *Wi*, *Ei*, *Fi* and *Ci* indicate the *i*th receiving/emitting elements locating in the south, north, west, east, flooring and ceiling surfaces, respectively. In contrast to the classical algorithms(exhibited in Figure 1(b)), we eliminated the C1 owning to the fact that power received by all the ceiling elements from LED source is 0. This is because every angle ϕ for this case is $\pi/2$. And the removal of those horizontal arrows demonstrated that each group of elements only receives reflecting energy from the rest groups of elements. It is notable that the simplification method doesn't worsen the calculation accuracy since it just excludes the redundant computation elements. The accuracy of the algorithm is only dependent on the numbers of elements in every reflection and the time slot which are concerned. Figure 1(c) illustrates the saved computation of the proposed algorithms. It can be implied that more fraction of elementary computations for higher reflections can be excluded in the simplified algorithm.

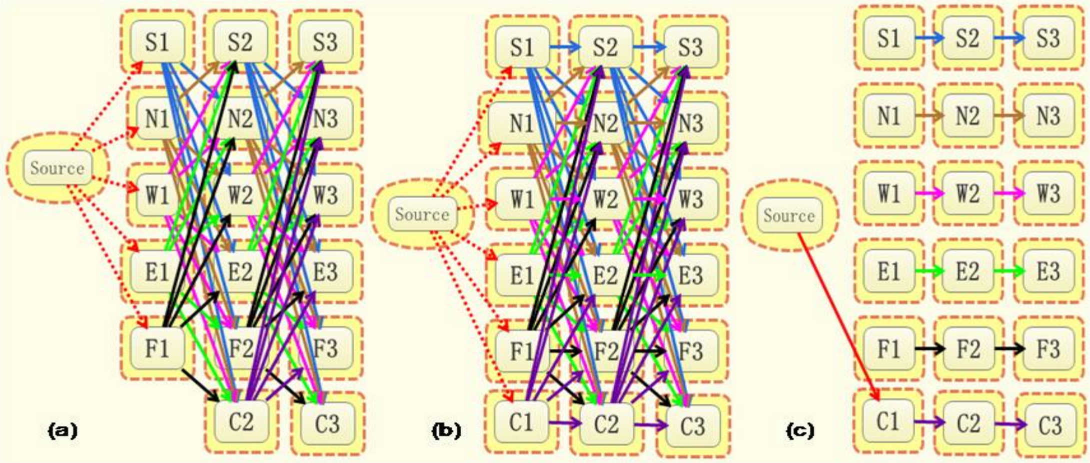

Figure 1: Schematic diagram of the relationship between emitting and receiving elements for (a) the simplified algorithms (b) the classical recursive algorithm and (c) saved elementary computations

B. *Elementary computaion of the proposed algorithms*

Let C_{Bi} and C_{Si} denote the elementary computations of classical recursive algorithm and proposed algorithm for *i*th reflection respectively. N_{Ti} indicates the total number of elements for *i*th reflection. N_{Fi} , N_{Ci} , N_{Si} , N_{Ni} , N_{Wi} , N_{Ei} denote the number of elements for the *i*th reflections on flooring, ceiling, south, north, west and east surface. C_{Bi} and C_{Si} can be given by:

$$C_{B1}=N_{T1} \tag{7}$$

$$C_{B2}=N_{T1}\times N_{T2} \tag{8}$$

$$C_{B3}=N_{T1}\times N_{T2}\times N_{T3} \tag{9}$$

$$C_{S1}=N_{T1}-N_{C1} \tag{10}$$

$$C_{S2}=N_{F1}(N_{T2}-N_{F2})+N_{S1}(N_{T2}-N_{S2})+N_{N1}(N_{T2}-N_{N2})$$
$$+N_{E1}(N_{T2}-N_{E2})++N_{W1}(N_{T2}-N_{W2}) \tag{11}$$

$$C_{S3}=N_{C2}(N_{T1}-N_{C1})(N_{T3}-N_{C3})+N_{F2}(N_{T1}-N_{F1}-N_{C1})$$
$$(N_{T3}-N_{F3})+N_{S2}(N_{T1}-N_{S1}-N_{C1})(N_{T3}-N_{S3})+$$
$$N_{N2}(N_{T1}-N_{N1}-N_{C1})(N_{T3}-N_{N3})+N_{E2}(N_{T1}-N_{E1}-N_{C1})$$
$$(N_{T3}-N_{E3})+N_{W2}(N_{T1}-N_{W1}-N_{C1})(N_{T3}-N_{W3}) \tag{12}$$

Let P_i denotes the ratio of the saved elementary computation of the proposed algorithm for different reflection times. It can be represented by C_{Si} and C_{Bi}:

$$P_1=1-C_{S1}/C_{B1} \tag{13}$$

$$P_2=1-C_{S2}/C_{B2} \tag{14}$$

$$P_3=1-C_{S3}/C_{B3} \tag{15}$$

The parameters are the same with the Configuration A in [12], and Table I summarizes the number of elements in each group for different reflections.

IV. THE RESULTS OF IMPULSE RESPONSE USING PROPOSED ALGORITHM

Table II gives the elementary computations for both algorithms developed from Eq.(7)-(15). Figure 2 points out the percentage of reduced computations with the proposed algorithm for different reflections. It is shown that the excluded computations increase as a function of the reflections. This makes sense in that more portions of elementary computations in the later reflections can be omitted by the simplified algorithm. For the impulse response of the first reflection, the eliminated computations are the parts relative to all the ceiling elements. If each surface is composed of the same numbers of elements, the fraction of deleted computations would be 1/6. In fact, since the rate of the ceiling elements to the total elements is larger than 1/6, the presented algorithm enables more proportion of saved calculation than 16.7%. Employing the parameters with the Configuration A in [12], the percentage of excluded calculations is 22.7%, 35.3% for the first and second reflection respectively, and it reaches to nearly 50% when the third reflections are concerned. And it could be implied that more portion of calculation could be excluded using the proposed algorithm.

Figure 4 demonstrates the impulse response simulated by the simplified algorithm, which agrees with the ones carried out by the classical recursive algorithm, shown in Figure 3. The fact that the residual sum of square between Figure 3 and Figure 4 is zero manifests that the proposed algorithm just removes some of the unnecessary calculations, without involving lower accuracy. As long as the spatial resolution (i.e., the minimum element on surfaces) and time resolution (time slot) for different reflections keeps unchanged, the accuracy of the simplified algorithm maintains the same with the classical recursive algorithm.

Furthermore, the proposed algorithm can be employed in both VLC and IR channels to examine impulse response. When dealing with VLC impulse response, the reduced calculation percentage remains the same, however the whole time saved could be substantial for the reason that there are often several hundred or even thousands of LED sources in VLC.

V. CONCLUSION

A simplified method is demonstrated for evaluating indoor optical impulse response based on recursive algorithm. This approach reduces the redundant content of the calculation while retains the same accuracy with classical recursive algorithm. The rate of saved elementary computation is nearly 50% for the third reflections and would be higher when more reflections are concerned.

TABLE I. NUMBER OF ELEMENTS ALONG DIFFERENT AXIS AND SURFACES FOR K REFLECTIONS

K	***Nx***	***Ny***	***Nz***	***Nc***	***Nf***	***Ns***	***Nn***	***Ne***	***Nw***	***Nt***
1	500	500	300	2.5×10^5	2.5×10^5	1.5×10^5	1.5×10^5	1.5×10^5	1.5×10^5	1.1×10^6
2	100	100	60	1.0×10^4	1.0×10^4	6.0×10^3	6.0×10^3	6.0×10^3	6.0×10^3	4.4×10^4
3	25	25	15	6.25×10^2	6.25×10^2	3.75×10^2	3.75×10^2	3.75×10^2	3.75×10^2	2.75×10^3

TABLE II. ELEMENTARY COMPUTATIONS AND SAVED COMPUTATION PERCENTAGE FOR K REFLECTIONS

K	***1***	***2***	***3***
Elementary computation of classical recursive algorithm	1.1×10^6	4.84×10^{10}	1.331×10^{14}
Elementary computation of proposed algorithm	8.5×10^5	3.13×10^{10}	7.07125×10^{13}
Reduced computation of proposed algorithm	2.5×10^5	1.71×10^{10}	5.74025×10^{13}
Reduced computation percentage of proposed algorithm	22.7%	35.3%	46.8%

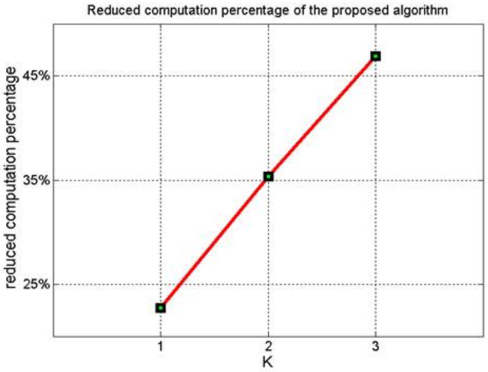

Figure 2: Saved computation percentage with respect to different reflections

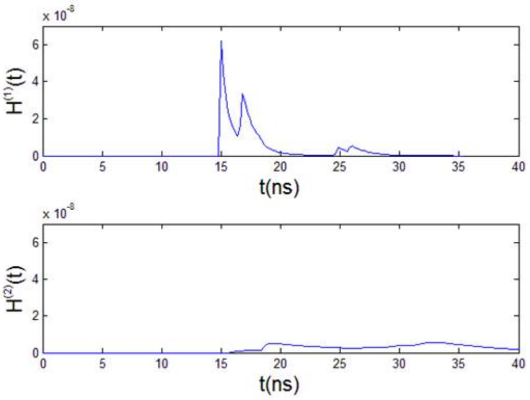

Figure 3: Simulation results of the impulse response employing the classical algorithm

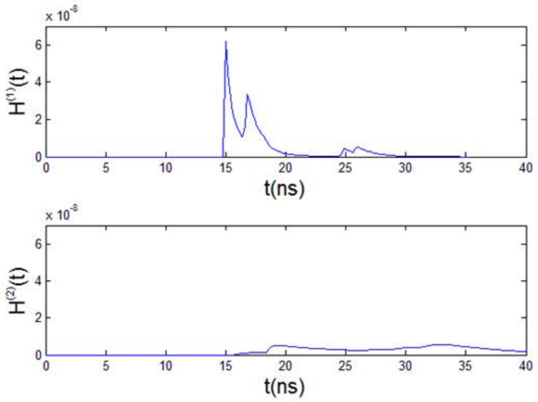

Figure 4: Simulation results of the impulse response employing the simplified algorithm

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