THE UNIVERSITY of LIVERPOOL

Ray-Tracing Programme

User's Manual

Jietao Zhang

Release 2002

============ USER MANUAL ============

I. Introduction

The 3D ray-tracing program is developed for radio channel prediction. The algorithm is based on Geometric Optics (GO) and Uniform Theory of Diffraction (UTD), in combination with image method [1][2][3]. Multiple reflections and transmissions, single diffraction, diffraction-reflection and reflection-diffraction mechanisms are included in the program. Given blueprint of the environment of interest, the ray-tracing program is capable of predicting both narrow- and wide-band parameters such as path loss and time-delay spread of radio channels. The result of studying the effects of building dielectric parameters on the prediction accuracy was published [4].

II. Running The Programme:

(1) Run Microsoft Developer Studio;
(2) Open workspace "c:\raytrace\raytrace.dsw";
(3) Select "Build" menu in Microsoft Developer Studio Toolbar;
(4) Click "Build Raytrace.exe" item;
(5) Press "Ctrl+F5" to run the program.

As the program starts running, the following options prompt on the screen:

(1) `Please enter the directory for input database:`

Here is to enter the directory on disk where the input database files are.
For example, if the database files are in "c:\raytrace\" directory, then "c:\\raytrace\\" should be input. The usage of "\\" in here is due to the inherent string process in VC++ software.

(2) `Please enter the directory for output files:`

Here is to enter the directory on disk where the output files will be.

It should be noted that the directory in which the output files are expected to saved must be created before executing the program. For example, if the user wants to put output files in the directory "c:\raytrace\output\", then this directory must be created before executing the program and "c:\\raytrace\\output\\" should be input at the prompts.

(3) `Please enter the TYPE OF SIMULATION: (0): Narrow-Band; (1) Wide-Band:`

Narrow-band: The program computes the Path loss only at each point;

Wide-band: The program computes both Path loss and time dispersion parameters.

If "0" is selected, received signal strength in decibels at each Rx point is saved in the corresponding output files. If "1" is selected, received signal strength, mean excess delay and RMS delay spread at each Rx point is saved in the corresponding output files.When "Wide-Band" option is selected, another two options will appear later on to specify some parameters for wide-band simulation. These options are

`Please enter the RECEIVER TIME RESOLUTION (ns):`

If the simulated transmitter has finite bandwidth, this parameter is to characterise its limited bandwidth effect. For example, if the transmitter bandwidth is 200 MHz, then 5 ns is input as its time resolution [5].

`Please enter the THRESHOLD (dB):`

When computing the time dispersion parameters, a threshold is required to specify the distinguishable multipath energy which is within a particular value of dBs below the maximum energy that is received [6]. 30 dB is a typical value as input, which indicates that those multiple energies within 30 dB below the maximum strength of the received ray are included in the calculation of time dispersion parameters.

(4) `Please enter the TYPE OF SCENARIO: (0): Microcell; (1): Picocell:`

Microcell: In this case, any facet in the environment is assumed as infinitely thick material with zero transmission coefficient. Thickness value specified in the database is not used in the calculation of material's reflection coefficient.

Picocell: In this case, any facet in the environment is assumed as finite thick material with its thickness specified in the database. Calculation of material's reflection and transmission coefficients are dependent on its thickness.

If "0" is selected, each facet in the database is assumed without transmittivity, i.e., the transmission coefficient of each facet is zero. This corresponds to outdoor microcellular channel simulation; if "1" is selected, each facet in the database has both reflectivity and transmittivity, and its reflection and transmission coefficients are calculated depending on the type of material defined in the database. This corresponds to indoor picocellular channel simulation.

(5) `Please enter the order of REFLECTION considered:`

Enter the order of reflection considered for at each simulation point. The higher order considered, the higher computation accuracy and higher computation time.

(6) `Please enter the order of DIFFRACTION considered:`

Enter the order of diffraction considered at each simulation point. In the program, either value "0" or "1" can be input. "0": no diffraction considered; "1": first-order diffraction considered.

(7) `Please enter the order of REF-DIF considered:`

Enter the order of ref-dif considered at each simulation point. In the program, either value "0" or "1" can be input. "0": no ref-dif considered; "1": first-order reflection-diffraction considered, which means a reflection followed by a diffraction occurs on the ray's journey from Tx to Rx.

(8) `Please enter the order of DIF-REF considered:`

Enter the order of dif-ref considered at each simulation point. In the program, either value "0" or "1" can be input. "0": no dif-ref considered; "1": first-order diffraction-reflection considered, which means a diffraction followed by a reflection occurs on the ray's journey from Tx to Rx.

III. Input Database Files:

Lfacet.dat: Input data of large facets (walls, ceilings and floors, etc.) and other simulation parameters;

Sfacet.dat: Input data of small facets (windows and doors, etc.);

Edge.dat: Input data of edges (corners and metallic window frames, etc.).

* The format of each input data file is described in Section in detail.

IV. Output Files:

AoA_phi.txt: Angle-of-arrival of each ray reaching Rx (ϕ component);

When only one location of Rx is specified in the database and wide-band simulation is performed, the angle of arrival at the Rx (ϕ component) is given in this file. There are $N \times 1$ elements in this file, with the number of rows N representing the number of incident rays at the Rx. (unit: radian)

AoA_theta.txt: Angle-of-arrival of each ray reaching Rx (θ component);

When only one location of Rx is specified in the database and wide-band simulation is performed, the angle of arrival at the Rx (θ component) is given in this file. There are $N \times 1$ elements in this file, with the number of rows N representing the number of incident rays at the Rx. (unit: radian)

Ref_1.txt: Intersection point locations of 1st order reflected ray;

When only one location of Rx is specified in the database, all intersection point locations of 1st order reflection are listed in the file. There are $N \times 3$ elements in this file, where N represents the total number of 1st order reflected rays. In each row, there are 3 columns representing the point location at x-, y-, and z-axis. (unit: metre)

Ref_2.txt: Intersection point locations of 2nd order reflected ray;

When only one location of Rx is specified in the database, all intersection point locations of 2nd order reflections are listed in the file. There are $N \times 6$ elements in this file, where N represents the total number of 2nd order reflected rays. In each row, there are 6 columns representing the point locations at x-, y-, and z-axis, with first 3 elements for the second reflection point and last 3 elements for the first reflection point. (unit: metre)

Ref_3.txt: Intersection point locations of 3rd order reflected ray;

When only one location of Rx is specified in the database, all intersection point locations of 3rd order reflections are listed in the file. There are $N \times 9$ elements in this file, where N denotes the total number of 3rd order reflected rays. In each row, there are 9 columns representing the point locations at x-, y-, and z-axis, with first 3 elements for the third reflection point, followed by 3 elements for the second reflection point, and last 3 elements for the first reflection point. (unit: metre)

Ref_4.txt: Intersection point locations of 4th order reflected ray;

The format is similar to Ref_1.txt, with 12 columns in each row.

Ref_5.txt: Intersection point locations of 5th order reflected ray;

The format is similar to Ref_1.txt, with 15 columns in each row.

Ref_6.txt: Intersection point locations of 6th order reflected ray;

The format is similar to Ref_1.txt, with 18 columns in each row.

Ref_7.txt: Intersection point locations of 7th order reflected ray;

The format is similar to Ref_1.txt, with 21 columns in each row.

Ref_8.txt: Intersection point locations of 8th order reflected ray;

The format is similar to Ref_1.txt, with 24 columns in each row.

Ref_9.txt: Intersection point locations of 9th order reflected ray;

The format is similar to Ref_1.txt, with 27 columns in each row.

Dif_1.txt: Intersection point locations of 1st order diffracted ray;

When only one location of Rx is specified in the database, all intersection point locations of 1st order diffraction are listed in the file. There are $N \times 3$ elements in this file, where N denotes the total number of 1st order diffracted rays. In each row, there are 3 columns representing the diffraction point location at x-, y-, and z-axis. (unit: metre)

Rd.txt: Intersection point locations of reflected-diffracted ray;

When only one location of Rx is specified in the database, all intersection point locations of 1st order reflection are listed in the file. There are $N \times 6$ elements in this file, where N denotes the total number of 1st order reflected-diffracted rays. In each row, there are 6 elements representing the point locations at x-, y-, and z-axis, with first 3 elements for the diffraction point and last 3 elements for the reflection point. (unit: metre)

Dr.txt: Intersection point locations of diffracted-reflected ray;

When only one location of Rx is specified in the database, all intersection point locations of 1st order reflection are listed in the file. There are $N \times 6$ elements in this file, where N denotes the total number of 1st order diffracted-reflected rays. In each row, there are 6 elements representing the point locations at x-, y-, and z-axis, with first 3 elements for the reflection point and last 3 elements for the diffraction point. (unit: metre)

E_number.txt: Number of various types of ray reaching the Rx;

There are $N \times 13$ elements in the file, with N representing the total number of Rx locations specified in the database. In each row, the 1st column denotes the number of direct ray (either 0 or 1); 2~10 columns denote the number of 1st order up to 9th order reflected rays; 11th column denotes the number of 1st order diffracted rays; 12th column denotes the number of reflected-diffracted rays; 13th column denotes the number of diffracted-reflected rays.

Disatance.txt: Tx-Rx separation in 3D space;

There are $N \times 1$ elements in the file, with N representing the total number of Rx locations specified in the database. Tx-Rx separation at each Rx location is given in each row. (unit: metre)

E_reference.txt Power at reference point (1m away from Tx);

There is 1 element in this file. The received power value at reference point is given. (unit: dB)

E_direct.txt: Power of direct ray (vector sum);

There are $N \times 1$ elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray at each Rx location is given in each row. (unit: dB)

E_tot_ref1.txt: Power of direct ray with 1st order reflected rays (vector sum);

There are $N \times 1$ elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray with 1st order reflected rays at each Rx location is given in each row. (unit: dB)

E_tot_ref2.txt: Power of direct ray up to 2nd order reflected rays (vector sum);

There are N $\times$ 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray with 1st–2nd order reflected rays at each Rx location is given in each row. (unit: dB)

E_tot_ref3.txt: Power of direct ray up to 3rd order reflected rays (vector sum);

There are N $\times$ 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray with 1st–3rd order reflected rays at each Rx location is given in each row. (unit: dB)

E_tot_ref4.txt: Power of direct ray up to 4th order reflected rays (vector sum);

There are N $\times$ 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray with 1st–4th order reflected rays at each Rx location is given in each row. (unit: dB)

E_tot_ref5.txt: Power of direct ray up to 5th order reflected rays (vector sum);

There are N $\times$ 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray with 1st–5th order reflected rays at each Rx location is given in each row. (unit: dB)

E_tot_ref6.txt: Power of direct ray up to 6th order reflected rays (vector sum);

There are N $\times$ 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray with 1st–6th order reflected rays at each Rx location is given in each row. (unit: dB)

E_tot_ref7.txt: Power of direct ray up to 7th order reflected rays (vector sum);

There are N $\times$ 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray with 1st–7th order reflected rays at each Rx location is given in each row. (unit: dB)

E_tot_ref8.txt: Power of direct ray up to 8th order reflected rays (vector sum);

There are N $\times$ 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray with 1st–8th order reflected rays at each Rx location is given in each row.

(unit: dB)

E_tot_ref9.txt: Power of direct ray up to 9th order reflected rays (vector sum);

There are N × 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from direct ray with 1st–9th order reflected rays at each Rx location is given in each row. (unit: dB)

E_ref.txt: Power of all simulated reflected rays (vector sum);

There are N × 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from all reflected rays at each Rx location is given in each row. (unit: dB)

E_tot_dif1.txt: Power of all 1st order diffracted rays (vector sum);

There are N × 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from the 1st order diffracted rays at each Rx location is given in each row. (unit: dB)

E_rd.txt: Power of reflected-diffracted rays (vector sum);

There are N × 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from the reflected-diffracted rays at each Rx location is given in each row. (unit: dB)

E_dr.txt: Power of diffracted-reflected rays (vector sum);

There are N × 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from the diffracted-reflected rays at each Rx location is given in each row. (unit: dB)

E_dif.txt: Power of all diffraction related rays (vector sum);

There are N × 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from the 1st order diffracted rays, reflected-diffracted rays and diffracted-reflected rays at each Rx location is given in each row. (unit: dB)

E_total.txt: Power of all simulated rays (vector sum);

There are N × 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from all rays considered at each Rx location is given in each row. (unit: dB)

E_pow_direct.txt: Power of direct ray (power sum);

Output format of the file refers to "e_direct.txt".

E_pow_ref1.txt: Power of all 1st order reflected rays (power sum);

There are N × 1 elements in this file, with N representing the total number of Rx locations specified in the database. The received power from all 1st order reflected rays at each Rx location is given in each row. (unit: dB)

E_pow_ref2.txt: Power of all 2^{nd} order reflected rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_ref3.txt: Power of all 3^{rd} order reflected rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_ref4.txt: Power of all 4^{th} order reflected rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_ref5.txt: Power of all 5^{th} order reflected rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_ref6.txt: Power of all 6^{th} order reflected rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_ref7.txt: Power of all 7^{th} order reflected rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_ref8.txt: Power of all 8^{th} order reflected rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_ref9.txt: Power of all 9^{th} order reflected rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_dif1.txt: Power of all 1^{st} order diffracted rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_rd.txt: Power of all reflected-diffracted rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_dr.txt: Power of all diffracted-reflected rays (power sum);

Format of the file refers to "e_pow_ref1.txt".

E_pow_total.txt: Power of all simulated rays (power sum);

Format of the file refers to "e_total.txt".

RMS_delay_spread0.txt: mean delay spread $\bar{\tau}$ and RMS delay spread τ_{rms} with infinite time resolution;

Only when the wide-band simulation is performed, the time dispersion parameters are computed. There are N $\times$ 2 elements in this file, with N representing the total number of Rx locations specified in the database. In each row, the mean excess delay and RMS delay spread are given. (unit: ns)

RMS_delay_spread1.txt: mean delay spread $\bar{\tau}$ and RMS delay spread τ_{rms} with user defined time resolution;

Format of the file refers to "RMS_delay_spread0.txt".

Pow_delay.txt: Power delay profile at a single Rx position.

When only one location of Rx is specified in the database and wide-band simulation is performed, the power delay profile at Rx is given in this file. There are N $\times$ 7 elements in the file, with N representing the total number of rays arriving at Rx. The 1st column in each row denotes the time-delay of each ray with respect to the direct ray in ns. The 2nd and 3rd columns denote the complex received electric field (real-part and imaginary-part) in the x-direction. The 4th and 5th columns denote the complex received electric field in the y-direction. The 6th and 7th columns denote the complex received electric field in the z-direction. (unit: v/m).

* Note:

(1) If "iRow = 1" and "iCol = 1" are set in the input data file "Lfacet.dat", then only one Rx location is specified in the database.

(2) The definitions of vector sum and power sum are described in Appendix A.

V. Database description:

(1) Lfacet.dat:

Each facet in 3D space is described by a rectangle defined by its corner location (**W**), two vectors specifying its width (**U**) and height (**V**), and the unit normal vector of the facet ($\hat{\mathbf{n}}$), as shown in the Fig.1 below, where $\hat{\mathbf{n}} = \dfrac{\mathbf{U} \times \mathbf{V}}{\left| \mathbf{U} \times \mathbf{V} \right|}$.

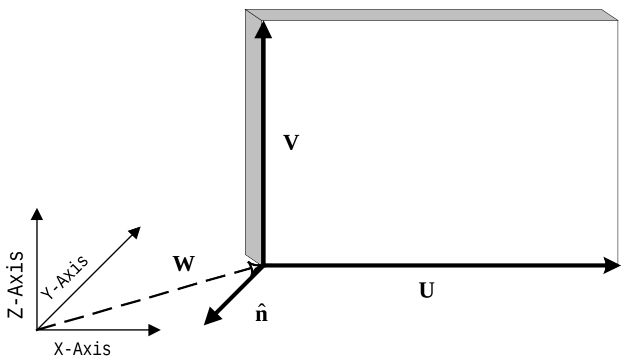

Fig.1. Definition of a large facet.

Format of the file:

1st row: Tx position: [x_t, y_t, z_t];

2nd row: Initial Rx position: [x_r, y_r, z_r];

3rd row: [iRow, iCol, dStepx, dStepy];

iRow:	Number of Rx positions in *y*-direction;
iCol:	Number of Rx positions in *x*-direction;
dStepx:	Resolution of Rx movement in *x*-direction (unit: metre);
dStepy:	Resolution of Rx movement in *y*-direction (unit: metre);

4th row: [dFreq, iTx_Type, iRx_Type, iTx_Orient, iRx_Orient, dPower];

dFreq:	Frequency of simulation (unit: MHz);
iTx_Type:	Antenna type of Tx:
	value "1": isotropic antenna;
	value "2": λ/2 dipole antenna;
iRx_Type:	Antenna type of Rx:
	value "1": isotropic antenna;
	value "2": λ/2 dipole antenna;
iTx_Orient:	Orientation of Tx:
	value "1": steered at *z*-direction;
	value "2": steered at *x*-direction;
	value "3": steered at *y*-direction;
iRx_Orient:	Orientation of Rx:
	value "1": steered at *z*-direction;
	value "2": steered at *x*-direction;
	value "3": steered at *y*-direction;
dPower:	Input power to the Tx (unit: w);

5th row: [iLfacet_Number, iLfacet_Col];

iLfacet_Number:	Total number of large facets in the file;
iLfacet_Col:	Total elements for a large facet description (fixed at 17);

6th row and onwards: Description of each large facet in the file:

[**W** (3 elements), **U** (3 elements), **V** (3 elements), $\hat{\mathbf{n}}$ (3 elements), ε_r , σ (unit: s/m), Thickness (unit: m), Type-of-facet, Facet No.];

Type-of-facet:	value "0": same medium as in which radio propagates;
	value "1": half-infinite medium;
	value "2": single-layer medium;
	value "3": single-layer medium backed by metal plate;
	value "4": metal plate.

(2) Sfacet.dat:

Each small facet in 3D space is defined in the same way as for the large facets. In the database, windows and doors are classified as small facets, while walls, floors and ceilings are classified as large facets. The small facets are physically attached on the large facets.

<u>Format of the file:</u>

1st row: [iSfacet_number, iSfacet_Col];

iSfacet_Number: Total number of small facets in the file;

iSfacet_Col: Total elements for a small facet description (fixed at 14);

2nd row and onwards: Description of each small facet in the file:

[**W** (3 elements), **U** (3 elements), **V** (3 elements), ε_r , σ (unit: s/m), Thickness (unit: m), Type-of-facet, Facet No.];

*Note: (1) Definition of the type of small facets is the same as for the large facets.
(2) Facet No. is the No. of large facet on which the small facet is attached.

(3) Edge.dat:

Fig.2 shows the definition of an edge. Each edge in 3D space is defined by a straight line segment with its starting point ($\mathbf{W_s}$) and end point ($\mathbf{W_e}$). Information of the two facets (called o-face and n-face) forming the edge is also described in this input data file. The angle formed by these two facets is α, which is related to a parameter n as $\alpha = (2-n)\pi$. For example, if the angle formed by two perpendicular walls is $90°$, then $n = 1.5$. The designation of which facet should be called the o-face and which the n-face is arbitrary. However, definitions of the unit vector tangential to the edge ($\hat{\mathbf{e}}$), the normal unit vector of the o-face ($\hat{\mathbf{n}}_o$) and the unit vector tangential to the o-face ($\hat{\mathbf{t}}_o$) should meet the criteria that $\hat{\mathbf{t}}_o = \hat{\mathbf{n}}_o \times \hat{\mathbf{e}}$. The direction of $\hat{\mathbf{e}}$ should be such that $\hat{\mathbf{t}}_o$ points towards the o-face as shown in the figure.

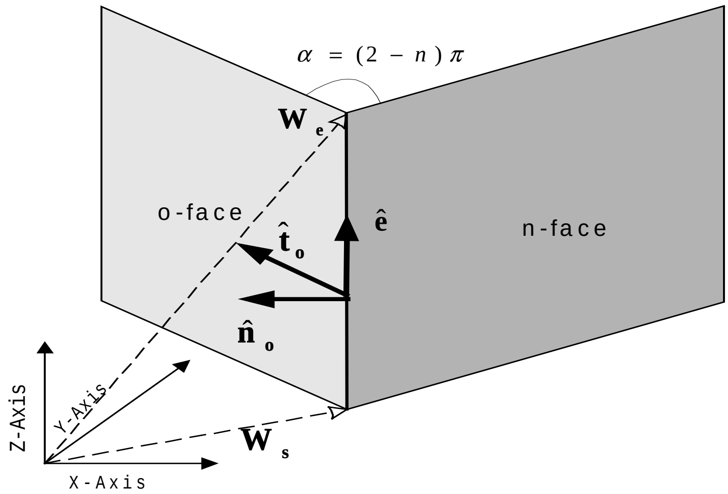

Fig. 2. Definition of an edge.

Format of the file:

1st row: [iEdge_number, iEdge_Col];

iEdge_Number: Total number of edges in the file;

iEdge_Col: Total elements for an edge description (fixed at 21);

2nd row and onwards: Description of each edge in the file;

[$\mathbf{W}_s$ (3 elements), $\mathbf{W}_e$ (3 elements), $\hat{\mathbf{n}}_o$ (3 elements), $\hat{\mathbf{e}}$ (3 elements), n , parameters of o-face (4 elements), parameters of n-face (4 elements)];

*Note: Parameters of o-face (n-face): Type-of-facet, ε_r , σ , Thickness.

VI. An Example of Database Description:

Example: To model a T-shape corridor environment. The top view of the scenario is shown in Fig. 3. Each concrete wall is 4-m high, with $\varepsilon_r = 5.0$, $\sigma = 0.02$ s/m, and $d = 0.10$ m. Each window is 2-m high located at 1-m height above the floor level, with $\varepsilon_r = 4.0$, $\sigma = 0$ s/m, and $d = 0.005$ m.

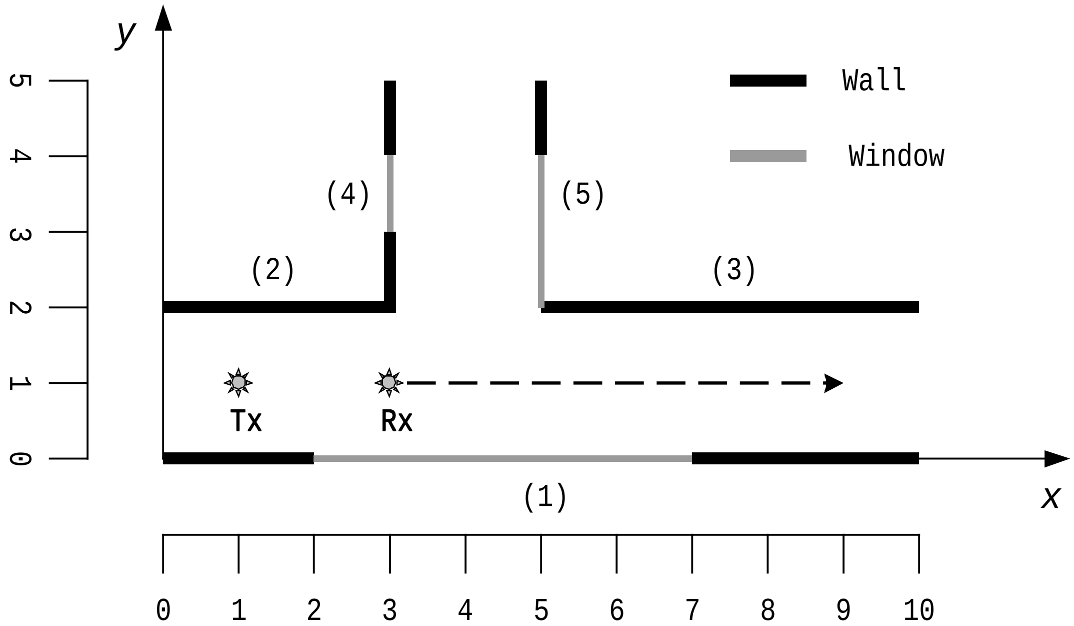

Fig. 3. Simulation scenario

Assume: Tx position [1, 1, 3];

Rx initial position [3, 1, 2];

Route of Rx: along *x*-direction up to *x* = 9 m, in 0.1 m each step;

Tx and Rx antenna: $\lambda/2$ dipole antennas;

Tx and Rx orientation: steered in *z*-direction;

Operating frequency: 1.8 GHz;

Input power to Tx: 1 w.

Description of the large facets, small facets and edges are shown below:

Lfacet.dat

```
   1    1    3
   3    1    2
   1   61  0.1    1
1800    2    2    1    1    1
   5   17
   0    0    0   10    0    0    0    0    4    0   -1    0   5.0  0.02  0.10   2   1
   0    2    0    3    0    0    0    0    4    0   -1    0   5.0  0.02  0.10   2   2
   5    2    0    5    0    0    0    0    4    0   -1    0   5.0  0.02  0.10   2   3
   3    2    0    0    3    0    0    0    4    1    0    0   5.0  0.02  0.10   2   4
   5    2    0    0    3    0    0    0    4    1    0    0   5.0  0.02  0.10   2   5
```

Sfacet.dat

```
  3    14
  2     0    1      5    0    0      0    0    2      4.0   0.0   0.005     2     1
  3     3    1      0    1    0      0    0    2      4.0   0.0   0.005     2     4
  5     2    1      0    2    0      0    0    2      4.0   0.0   0.005     2     5
```

Edge.dat

```
 2   21
 3  2  0    3  2  4    0 -1  0    0  0  1    1.5    2   5.0   0.02   0.10    2   5.0   0.02  0.10
 5  2  0    5  2  4   -1  0  0    0  0  1    1.5    2   4.0   0.00  0.005    2   5.0   0.02  0.10
```

If both floor and ceiling are considered, four more facets are included in the Lfacet.dat file. Assuming the floor and ceiling are single-layer dielectric slabs with constitutive parameters $\varepsilon_r = 7.0$, $\sigma = 0.2$ s/m, and $d = 0.25$ m, and are backed by metal plates, the new file is then modified as below. In this case, the other two files are not modified.

Lfacet.dat

```
   1    1    3
   3    1    2
   1   61  0.1    1
1800    2    2    1    1    1
   9   17
   0    0    0   10    0    0    0    0    4    0   -1    0    5.0  0.02  0.10    2    1
   0    2    0    3    0    0    0    0    4    0   -1    0    5.0  0.02  0.10    2    2
   5    2    0    5    0    0    0    0    4    0   -1    0    5.0  0.02  0.10    2    3
   3    2    0    0    3    0    0    0    4    1    0    0    5.0  0.02  0.10    2    4
   5    2    0    0    3    0    0    0    4    1    0    0    5.0  0.02  0.10    2    5
   0    0    0   10    0    0    0    2    0    0    0    1    7.0  0.20  0.25    3    6
   0    0    4   10    0    0    0    2    0    0    0    1    7.0  0.20  0.25    3    7
   3    2    0    2    0    0    0    3    0    0    0    1    7.0  0.20  0.25    3    8
   3    2    4    2    0    0    0    3    0    0    0    1    7.0  0.20  0.25    3    9
```

VII. An Example of Simulation:

As an example, the path loss characteristics of the radio wave propagation within a straight corridor is predicted by the model. The input database files for this simulation are enclosed. Configuration of the simulation is shown in Fig. 4. In this case, up to 8th order reflections are considered when predicting the path loss characteristics, and no diffraction is considered because of no edges are implemented in the database file.

```
Please enter the directory for input database :    E:\\RAYTRACE\\

Please enter the directory for output files :    E:\\RAYTRACE\\OUTPUT\\

The operating frequency:  1000 MHz
Number of large facets: 4
Number of small facets: 0
Number of edges: 0

Please choose the TYPE OF SIMULATION: (0): Narrow-Band; (1) Wide-Band :    0

Please choose the TYPE OF SCENARIO: (0): Microcell; (1): Picocell :    0

Please enter the order of REFLECTION considered :    8

Please enter the order of DIFFRACTION considered :    0

Please enter the order of REF-DIF considered :    0

Please enter the order of DIF-REF considered :    0
```

Fig. 4. Configuration of the simulation.

After the simulation, data in the files "e:\raytrace\output\e_direct.txt", "e:\raytrace\output\e_total.txt" and "e:\raytrace\output\distance" can be easily extracted using software EXCEL or MATLAB. The simulated received field strength is plotted in Fig. 5 against the transmitter-receiver separation. Chen [7] has developed a prediction model based on ray-launching method and investigated the wave behaviour in such case. His simulation result is plotted in Fig. 6 for comparison with the simulation from our ray-tracing model. Good agreements of the predicted path loss are observed. The difference in magnitude is due to different antennas gain used for simulations. Nevertheless, it is found that the results of two simulations are compared very well after normalisation of path loss in performed.

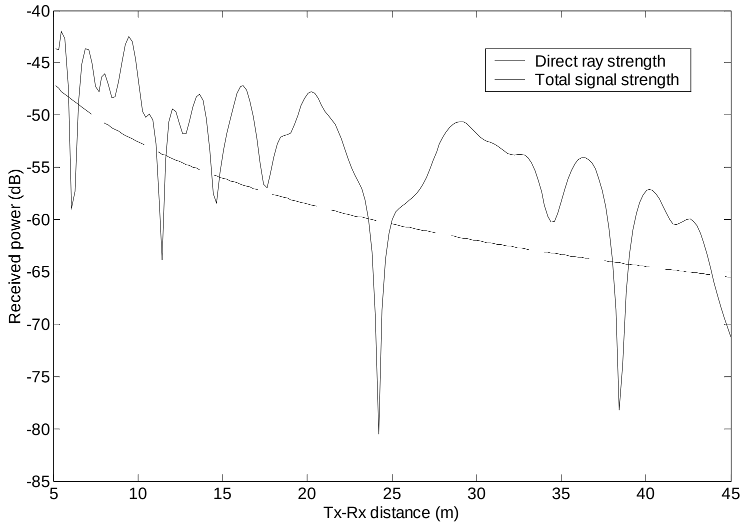

Fig. 5. Simulation result for the corridor scenario.

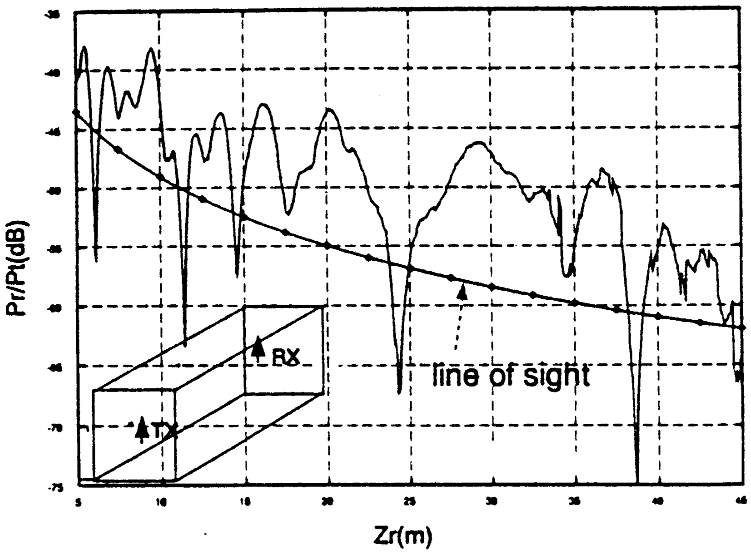

Fig. 6. Simulation result for the corridor scenario by Chen [7].

Appendix A: Vector sum vs. Power sum

There are two types of summation generally used for the radio channel modelling. One is referred to vector summation, in which each received field is decomposed, using a common Cartesian coordinate system, into a triad of complex components $\mathbf{E}_x$, $\mathbf{E}_y$, and $\mathbf{E}_z$, and the total received field $\mathbf{E}_{tot}$ is obtained by adding all the respective components of each ray. Mathematically, assuming N rays arrive at the receiver, the received field vector can be expressed as

$$\mathbf{E}_{tot} = \left(\sum_{i=1}^{N}\mathbf{E}_{ix}\right)\hat{a}_x + \left(\sum_{i=1}^{N}\mathbf{E}_{iy}\right)\hat{a}_y + \left(\sum_{i=1}^{N}\mathbf{E}_{iz}\right)\hat{a}_z$$

where $\hat{a}_x$, $\hat{a}_y$ and $\hat{a}_z$ are unit vectors in x-, y- and z-direction. The corresponding receiver field strength can therefore be given by

$$E_{tot} = \sqrt{\left|\sum_{i=1}^{N}\mathbf{E}_{ix}\right|^2 + \left|\sum_{i=1}^{N}\mathbf{E}_{iy}\right|^2 + \left|\sum_{i=1}^{N}\mathbf{E}_{iz}\right|^2}$$

The other type of summation is referred to power summation, in which the received field strength E_{tot} is obtained by adding the individual field strength of each ray as

$$E_{tot} = \sum_{i=1}^{N} E_i = \sum_{i=1}^{N}\sqrt{\left|\mathbf{E}_{ix}\right|^2 + \left|\mathbf{E}_{iy}\right|^2 + \left|\mathbf{E}_{iz}\right|^2}$$

In the vector sum process, the received electric field is vectorially combined field associated with each ray arriving at the receiver, and hence can account for the small-fading phenomenon. In the power sum process, the vectorially combined field is smoothed out by adding incoherently the strength of each ray. Thus, it is used to account for the received field in wide-band system.

Appendix B: Path loss calculation

The received power at the receiver is defined as

$$\mathrm{P}_R = \mathrm{P}_T \cdot \left(\frac{\lambda}{4\pi} \left| E_{tot} \right| \right)^2$$

where P_T denotes the transmitter power and λ is the wavelength. The effects radiation patterns of both the transmitter and receiver are inherently included in the calculation of received electric field strength $\left| E_{tot} \right|$. In the ray-tracing model, $E_r = 0.0$, $E_\theta = 1.0$ and $E_\phi = 0.0$ are used to compute the radiation pattern of an isotropic antenna; and $E_r = 0.0$, $E_\theta = \frac{\cos\left(\pi \cos\theta / 2\right)}{\sin\theta}$ and $E_\phi = 0.0$ are used to compute the radiation pattern of a half-wavelength dipole antennas. The path loss in decibels is expressed as

$$\mathrm{PL}(\mathrm{dB}) = \mathrm{P}_{ref}(\mathrm{dB}) - \mathrm{P}_R(\mathrm{dB})$$

where $\mathrm{P}_{ref}(\mathrm{dB})$ denotes the received power at reference point (1 metre away from the transmitter). This quantity is shown in the output file "e_reference.txt".

Appendix C: Definitions of Mean excess delay and RMS delay spread

The power delay profile, which gives the time distribution of the received signal power from a transmitted δ-pulse, is defined as [6]

$$P(\tau) = |h(\tau)|^2 = \sum_{k=1}^{N} a_k^2 \, \delta(\tau - \tau_k)$$

The time dispersive properties of wideband multipath channels are most commonly quantified by their mean excess delay ($\overline{\tau}$) and RMS delay spread (τ_{rms}). The mean excess delay is the first moment of the power delay profile and is defined as

$$\overline{\tau} = \frac{\sum_k P(\tau_k)\tau_k}{\sum_k P(\tau_k)} = \frac{\sum_k a_k^2 \tau_k}{\sum_k a_k^2}$$

The RMS delay spread is the square root of the second central moment of the power delay profile and is defined to be

$$\tau_{rms} = \sqrt{\overline{\tau^2} - (\overline{\tau})^2}$$

where

$$\overline{\tau^2} = \frac{\sum_k P(\tau_k)\tau_k^2}{\sum_k P(\tau_k)} = \frac{\sum_k a_k^2 \tau_k^2}{\sum_k a_k^2}$$

References:

[1] D. A. McNamara, C. W. I. Pistorius, and J. A. G. Malherbe, *Introduction to The Uniform Geometrical Theory of Diffraction*, London: Artech House, 1990.

[2] M. F. Catedra, *Cell Planning for Wireless Communications*, Boston: Artech House Publishers, 1999.

[3] S. Naruniranat, "A Three-dimensional Image Ray Tracing Method for Indoor Wireless Channel Characterisation," *Ph.D. thesis*, University of Liverpool, 2000.

[4] J. Zhang and Y. Huang, "Indoor Channel Characteristics Comparisons for The Same Building With Different Dielectric Parameters," *IEEE 2002 International Conference on Communications*, NY, USA, April, 2002.

[5] H. Hashemi, "Impulse Response Modelling of Indoor Radio Propagation Channels," *IEEE Journal on Selected Areas in Communications*, Vol. 11, No. 7, pp. 967-978, September, 1993.

[6] T. S. Rappaport, *Wireless Communications: Principles & Practice*, Prentice-Hall, Inc., 1996.

[7] S. H. Chen and S. K. Jeng, "An SBR/Image Approach for Indoor Radio Propagation in a Corridor," *IEICE Transactions on Electronics*, Vol. E78-C, No. 8, pp. 1058-1062, August, 1995.