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효율적 다중경로 전파 예측을 위한 Ray-Tracing의 개선된 벡터 표현법

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An efficient multipath propagation prediction using improved vector representation

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요 약

본 논문은 정확한 전파 모델과 신속한 전파 예측 모델을 필요로 하는 다중 경로 현상을 효과적으로 획득하기 위해 효율적인 데이터 표현 구조를 제안한다. 본 논문은 ray tracing에서 사용되고 있는 VR(Vector Representation)을 향상시키기 위한 데이터 표현 구조로서, 빌딩과 같은 오브젝트를 표현하기 위해 CR(Circular Representation)을 이용하는 오브젝트 표현 방법을 제안한다. 제안된 CR은 건물의 중심에서 건물을 둘러 싸도록 원을 그리는 형태이다. 본 구성에서 CR은 기하학적 구조를 위한 기본 빌딩 구조로서의 기능을 가지며, VR이 단독으로 사용되어 졌을 때보다 더 많은 효율성을 증진시킨다. VR은 건물을 표현하기 위해 여러개의 벽면 벡터를 필요로 하는 반면, CR은 하나의 원으로 표현된다. 결과적으로 제안된 방법에 의해 ray tracing에서 상당한 양의 계산 비용을 줄일 수 있다. 본 논문의 목표는 효율적인 ray tracing 예측 모델을 위해 데이터 구조화 시에 효율성을 얻기 위한 해결책으로서 CR을 제안하는 것이다. 본 논문은 제안된 방법에 의해 계산 부하량이 현저하게 줄어듬을 보인다. 또한 deterministic ray tracing 모델에서 CR의 계층적 구조의 수반 가능한 사용을 보인다. 시뮬레이션 결과는 계층적 octree 구조가 약 50%의 계산 부하를 감소시키고 있는 반면 본 논문에서 제안된 CR은 분산된 물체의 수에 비례하여 계산 부하량을 현저하게 감소시킨다는 것을 나타낸다.

ABSTRACT

In this paper, we introduce a highly efficient data structure that effectively captures the multipath phenomenon needed for accurate propagation modeling and fast propagation prediction. The proposed object representation procedure is called 'circular representation (CR)' of microwave masking objects such as buildings, to improve over the conventional vector representation (VR) form in fast ray tracing. The proposed CR encapsulates a building with a circle represented by a center point and radius. In this configuration, the CR essentially functions as the basic building block for higher geometric structures, enhancing the efficiency more than when VR is used alone. The simulation results indicate that the proposed CR scheme reduces the computational load proportionally to the number of potential scattering objects while its hierarchical structure achieves about 50% of compuational load reduction in the hierarchical octree structure.

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I. Introduction

Wireless communication system is expanding rapidly as it provides personal convenience to users in this ever-growing and fast-paced society. As the volume of hand phone users surges, the cell size of the transmitting base station needs to be optimized to accommodate the increased spectrum requirement. For very small-sized cells covering ranges of less than 1 km, the data based on the statistical analysis of measured path-loss in a classical empirical model shows considerable mismatch, especially in dense urban environment cluttered with various sizes and shapes of building structures. Figure 1 depicts a frame of cell design tool that shows the 3-D plot of propagation loss of a transmitter at base station due to diverse masking objects and ranging in an urban area. Therefore, for practical cell design application targeting urban areas, a sophisticated path-loss prediction model is required to determine an effective antenna location, which would minimize both the region of poor coverage and the overlapped areas among adjoining antennas. For this purpose, a deterministic model is widely used. Supported by ray-tracing algorithms, the deterministic model traces radio waves propagating from a base station to a mobile station and guarantees adequate accuracy. However, it is well known that a deterministic model requires high computational costs in time. The cost increases exponentially with the number of walls and edges presenting potential scattering objects and with the number of interactions which include reflection and diffraction. Furthermore, in predictions for realistic 3-dimensional environments, the high complexity of computation becomes a severe problem. Many researchers have tried to reduce the computational complexity either by predicting only within 2 dimensions, or by using hybrid techniques. In the hybrid techniques, the object database is held in 2 dimensions while the ray-tracing algorithm is applied in 3 dimensional coordinate system[1].

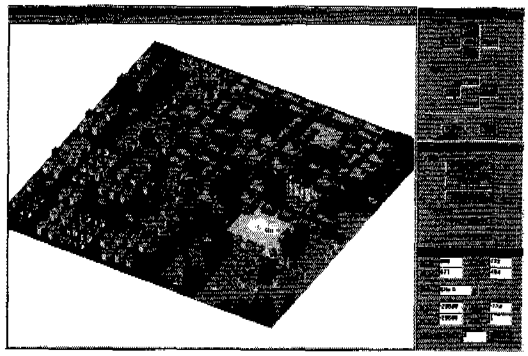

Fig 1. A frame of cell design tool analyzing propagation path-loss in an urban areas.

Computational time is a very critical problem in cell design application. In practical situations, cell design application targets large prediction area including several cells, and predicts propagation under various conditions in order to arrange antennas optimally. If the prediction is performed during the wrong conditions, using a deterministic model with its huge computational time may be a waste of time. As a result, it is essential to reduce the computational load in the ray-tracing procedure to ensure the practical use of the deterministic model.

Various efforts have been made in the past focused to computational load reduction in ray tracing. Yun[2] showed how to generate visibility lists in order to make the problem simple. Wolfle[3] proposed reduction techniques including the simplification of building structures, hierarchical box structures, fresnel zone limitations and pixel separation, while Foley[4] proposed hierarchical octree structure. These approaches are classified two different ways: (i) intelligent strategies to find ray paths quickly and (ii) algorithms to reduce the number of potential scattering objects in the computation.

The main focus of this paper is to achieve the computational load reduction by incorporating the proposed CR. In ray tracing, each building object is depicted in the form of vector representation (VR) to examine ray wall intersections with ease. It means that it takes a collection of several vectors depicting a wall of a building to represent a building. Naturally, the number of vectors depends on the planar shape of building. In this application, we propose the Circular Representation (CR) method that indicates a building with a set of circular parameters, a center and a radius. Essentially, only these two parameters are needed regardless of the shape of the building. By using the constraints with parameters of CR, the buildings without potential scattering walls are eliminated before furthering it to a detailed process to find the ray-wall intersections. As a result, the computational load decreases significantly. Furthermore, our simulations show that the hierarchically structured CR achieves more computational load reduction than any other (non-CR) hierarchical structures.

The content of this paper is as follows. In Section II, the prediction procedure in the deterministic model is presented. In Section III, the proposed circular representation is described. In Section IV, hierarchical CR is presented. And, finally, in Section V we show the results of the performance comparison between proposed CR and conventional VR.

II. Propagation Prediction Procedure in the Deterministic Model

Figure 2 shows a block diagram of the deterministic propagation prediction model. The whole procedure can be divided into two parts: finding a path of the propagated wave and calculating the path loss along the path.

1. Geometry Database

The geometry database in the deterministic model is attained from a digitized map of a cell site. Conventionally, geometry data is stored in vector format, not raster format, as shown in Figure 3. It means that each building data in the geometry database has a vector representation which consists of a set of wall-vectors, a set of normal vectors of wall, or a set of corner points. They can be easily converted into each of the other forms. In this paper, it is assumed that VR is composed of a set of wall vectors.

2. Finding the path of propagation block (ray-tracing block)

This block simulates multipath phenomenon in microcell environment. In the cell, an RF signal propagates via various routes which include direct propagation, reflection and diffraction. To simulate this phenomenon between the base station and mobile station, their locations and geometry

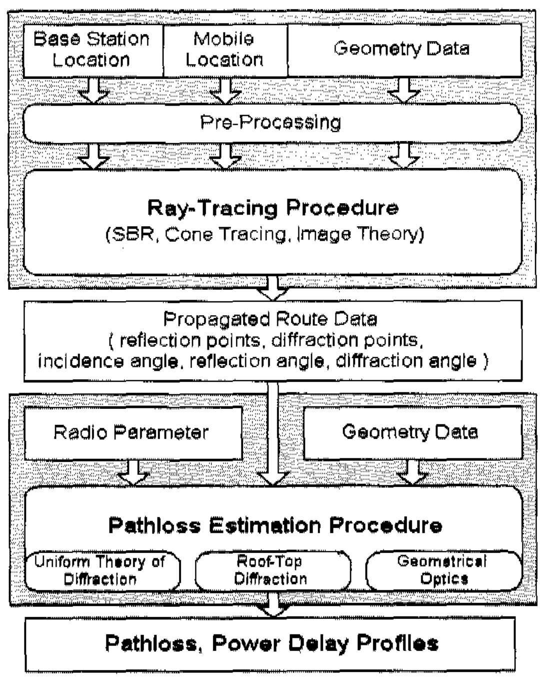

Fig 2. Path loss prediction using ray-tracing procedure block diagram

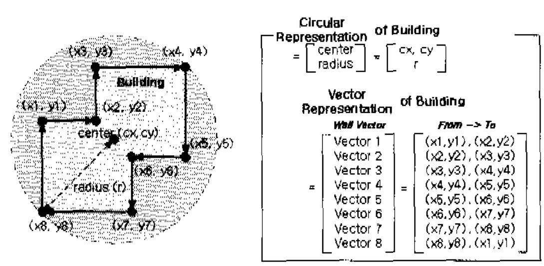

Fig 3. Vector representation and circular representation of building

database are used as input for the block in the upper portion of Figure 2. With this information, propagation routes of waves which are emitted from the base station and arrive at the mobile station are calculated via ray-tracing algorithms like that of Shooting and Bouncing Ray (SBR) [5],[6], Cone Tracing[7],[8], or Image Theory[9]. For example, when using the SBR algorithms, a ray is launched from 0 to 2π with very small angular separation (α) at the base station. It is tested to find whether or not the ray is received at the reception sphere of the mobile station.

3. Calculating path loss block

Once the route information is known, the propagation path-loss can be calculated. The calculation of path loss block requires the frequency information of the RF signal, electromagnetic characteristics of buildings, the dimensions of the street as well as propagation route information. The path loss calculation is performed with Geometrical Optics (GO) and Uniform Theory of Diffraction (UTD)[5],[9],[10],[11],[12]. From the route information, the propagating distance from base station to mobile station can be extracted and it is possible to calculate the power delay profile. The entire procedure is repeated for every mobile location to be predicted.

It should be noted that most of the computational time is consumed by the ray-tracing block.

In ray-tracing problem, the principal procedure is to locate the next reflection wall and diffraction corner. To find them, the ray-wall intersection should be examined. Just as in geometry data, the propagating ray is also represented in vector form with a set of origin (O_x, O_y) and directive angle (θ) or with a set of origin and very far point (f_x, f_y) in the direction of . In this paper, the ray vector is assumed as a segment between (O_x, O_y) and (f_x, f_y) as shown in Figure 4. Then, a ray-wall intersection test can be performed with four arithmetic operations[13],[14].

Ⅲ. Circular Representation of Building

Figure 3 shows the proposed CR of masking objects. CR encapsulates an object, especially a building in a deterministic model, with a circle described with center and radius. When the corner points of a building are known as $\{ (x_1, y_1), (x_2, y_2), \ldots, (x_i, y_i), \ldots, (x_M, y_M) \mid i = \textit{index of corner}, M = \textit{number of corners} \}$, the center of CR is

$$CR(c_x, c_y) = \left(\frac{1}{M}\sum_{i=1}^{M} x_i, \frac{1}{M}\sum_{i=1}^{M} y_i\right) \qquad (1)$$

and the radius of CR is

$$\begin{aligned} CR(c_x, c_y) &= \max(\|(x_i, y_i) - (c_x, c_y)\|) \qquad (2) \\ &= \max(\sqrt{(x_i - c_x)^2 + (y_i - c_y)^2}) \end{aligned}$$

in a simple form, where

$CR(c_x, c_y, r)$ ≡ *CR(center position, radius) of building*

M ≡ *number of corners in buildings*

i ≡ *index of corner*

In this configuration, CR manifests a higher geometrical structure of an object than VR. In geometric data, each building is composed of several walls. VR is in an inherently hierarchical structure wherein a collection of wall vectors representing walls make up a building by grouping the walls at an upper echelon of the structure. On the contrary, CR in itself represents buildings of different shapes at the same echelon without resorting to intermediate levels. Therefore, the ray-CR intersection screening checks preceding ray-wall intersection tests are able to considerably reduce the computational load by using certain constraints.

Employing the constraints for ray-CR intersection screening check is as follows. The distance between the center of CR and intersection point, *(int_x, int_y)*, in Figure 4 is determined by a simple calculation. If the distance is shorter than radius, it is ensured that VR in given CR is possible to intersect with the line.

Otherwise, VR doesn't intersect with the line and that VR can be kept out from the computation. By separating these buildings, the computational load can be made to decrease.

After an inspection with the above constraint, only those CRs overlapping with ray lines, not ray vectors, remain. It means that the CRs not overlapping with ray vectors also remain for further ray wall intersection tests. These unnecessary CRs are separated for elimination by employing the following constraint. For given CR and ray vectors, the radius and distance can be known from the above constraint. As shown in Figure 5, we can assume an imaginary CR, which is on the rear side of the ray vector and on which the origin of ray vector is located. Then, we can calculate the position of the intersection point (no_x, no_y), which is a distance, $\sqrt{radius^2 - dist^2}$, away from (o_x, o_y). For fewer computations, the distance can be assumed equal to the radius. If the line perpendicular to the ray vector and across the center of CR doesn't intersect with the segment, (no_x, no_y), (f_x, f_y), the VR in given CR never intersects with the ray vector and can be eliminated from further computation. This is the second constraint. The next two subsections address the two major problems in ray tracing in order to find the next reflection points and the next diffraction corner, respectively. The former involves finding the nearest obstructing wall problem while the latter basically entails the LOS/NLOS decision problem.

1. Finding the nearest obstructing wall problem

When the ray vector and VR of buildings are given, the procedure to find a wall where the next reflection occurs can be separated into two steps.

(i) For each building, the ray-tracing procedure checks whether or not the ray vector crosses over the wall vector.

(ii) Whenever an intersection is found, the procedure inspects whether or not the intersection point is the nearest one from the origin of the ray vector.

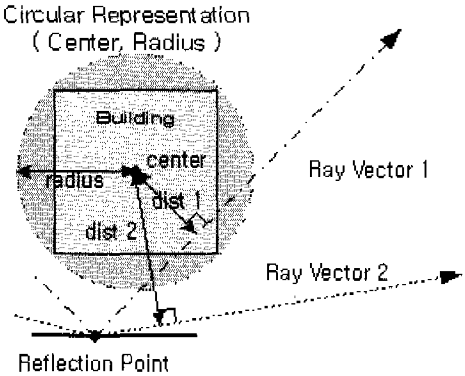

Fig 4. Constraint 1

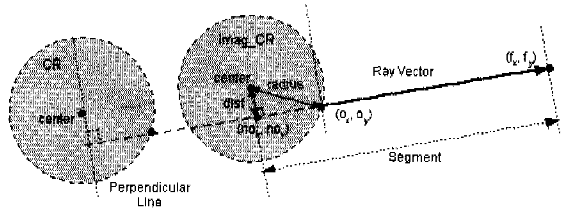

Fig 5. Constraint 2

If there are *N* buildings concerned in computation and the number of walls for every building is a constant *M*, then the problem has a computational complexity *O(MN)*. In this approach, *M* intersection tests are required for each building which doesn't cross over a ray vector. Proposed CR reduces the computational load by eliminating these unnecessary operations by using the constraint given above (e.g. *before Step (i)*).

For example, as shown in Figure 6, assume that there are three rectangular buildings for a ray-wall intersection test and three ray vectors propagate in different directions. Not considering CR, the ray-wall intersection is tested 12 times (e.g. *12 = (number of buildings=3)×(number of walls=4)*) for all ray vectors. But when considering the constraints with CR, test operations are reduced as follows. In the case of ray vector 1, which intersects only one building, three ray-CR intersection tests and four ray-wall intersection tests at *building1* are required. In the case of ray vector 2, which doesn't intersect any buildings, only three ray-CR intersections are tested. In the case of ray vector 3, which intersects all buildings, the number of test operations increases from 12 to 15 tests, composed of three ray-CR intersection screening tests and twelve ray-wall intersection tests. However, in a realistic microcell environment, the case occurrence of ray vector 3 is rare. As a consequence, it can be said that the approach with CR almost always reduces the computational load.

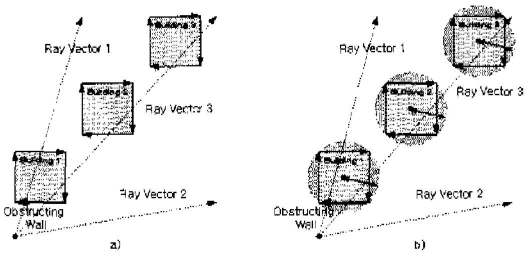

Fig 6. Ray-wall intersection: (a) without considering CR, (b) when considering CR.

2. LOS/NLOS decision between two positions

The LOS/NLOS decision problem is very similar to the previous problem of finding the nearest obstructing wall. The difference is that the LOS/NLOS decision problem does not need to find the 'nearest' wall. Instead it only needs to know whether the ray is obstructed with a wall vector. Thus, the decision procedure can break-out whenever the ray intersects with a wall. The computational load is the largest because no break-out happens in the procedure. At a NLOS condition, the computational load depends on the indexing sequence of buildings. If the obstructing building is indexed first, a very short time is consumed, but if it is indexed last, the time is about the same as the LOS case. These phenomenon occurs even when the CR is considered, but the time is significantly reduced as the simulation results show.

Ⅳ. Hierarchical Circular Representation

Figure 7 shows a hierarchical CR. Higher $(n+1)$ order CR consists of a few lower (n) order CR in close proximity to the following equations. The center is

$$CR^{n+1}(c_x, c_y) = [\frac{1}{M}\sum_{i=1}^{M} CR_i^n(c_x), \frac{1}{M}\sum_{i=1}^{n} CR_i^n(c_y)] \quad (3)$$

and the radius is

$$CR^{n+1}(r) = \max(\|CR^{n+1}(c_x, c_y) - CR_i^n(c_x, c_y)\| + CR_i^n(r)) \quad (4)$$

where n ≡ *order of hierarchical circular representation*

M ≡ *number of lower order circular representations CR^n in CR^{n+1}*

i ≡ *index of of lower order circular representations CR^n in CR^{n+1}*

For clarity, let us call the CR in Section III, which is derived from the VR, the 1st order CR. The building data in Figure 7 is then composed of VR, 1st, 2nd, and 3rd order CR. A simple way of generating hierarchical CR as follows.

(i) Similarly to hierarchical box structures or hierarchical octree structures, assume rectilinear grids and rectangular region are divided by them.

(ii) Group CRs of which the center exists in the same region.

(iii) Using the above Equations (3) and (4), compose a higher order CR for each

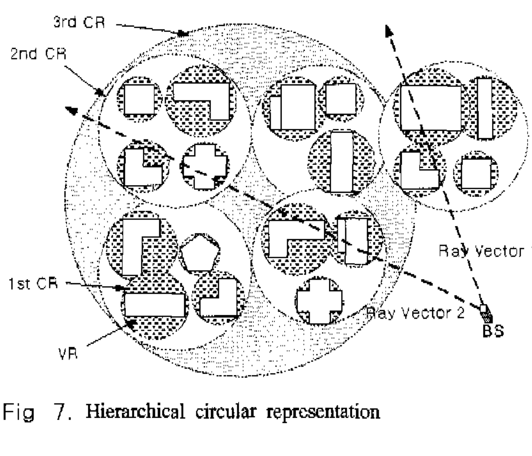

Fig 7. Hierarchical circular representation

region.

It is noted that the hierarchical CR is based on object partitions, while other hierarchical structures are based on space partitions.

Finding the ray-wall intersections with a hierarchical CR is very similar to the case of other hierarchical structures. If it is assumed that the highest order of building database is 3rd, the constraints given in Section III are first examined with the highest (e.g. 3rd) order CR. Then the ray-CR intersection tests with lower (e.g. 2nd) order CRs in higher order CR satisfying constraints are examined. The same procedure is repeated for lower (e.g. 1st) order CR and then, finally, the ray-wall intersection is found. A simulation shows that better computational efficiency could be obtained with a hierarchical CR.

V. Experimental Results

Experiments show the enhancement of computational efficiency. To show the reduction of computational load, three other simulations are executed. These simulations are performed in Pentium PC and Matlab v5.1. FLOPS(FLoating-point OPerationS) is used as the metric for performance.

1. The efficiency with respect to the number of scattering objects

Simulation results show the efficiencies of the CR when increasing the number of buildings and when increasing the number (e.g. complexity) of walls (and/or building). A geometric database for simulation is composed as follows. To investigate the performance enhancement relative to the number of buildings, four 2x2 buildings, sixteen 4x4 buildings and thirty-six 6x6 buildings are considered. For each case, buildings of varying shapes are employed as shown in Figure 8, such that the enhancement related to the complexity of building can be measured and compared. At first, the results of FLOPS to find the nearest obstructing wall only with VRs are computed. Then the results of FLOPS from a ray-CR intersection test followed by a ray-wall intersection test are computed. Table I shows the simulation results. For four-side buildings, we obtained reduction ratios about 5%, 30% and 40% for 4, 16 and 36 buildings, respectively. For six-side buildings, we obtained about 15%, 45% and 55% reduction ratios for four, sixteen and thirty-six buildings, respectively. From these results, it is evident that CR is more efficient when more scattering objects are considered in computation.

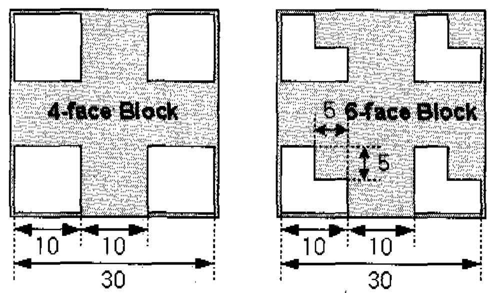

Fig 8. Two shapes of building for Simulation 1: (a) 4-face (b) 6-face

2. The efficiency with respect to the highest order of hierarchical circular representation concerned

A building database is composed as follows. As shown in Figure 9, each building is square shaped and a total of 144 buildings are distributed uniformly. Then, from the VR to the 3rd order CR are composed. Second (e.g. 3rd) order CR is composed with 2x2 1st (e.g. 2nd) order CRs. Hierarchical octree structures are also composed. We label the octree structure, which consists of 2x2 buildings similar to 2nd order CR, as the 2nd order octree structure. The octree structure, which consists of 2x2 2nd order octree structures, is similar to the 3rd order CR, as that of the 3rd order octree structure. In shooting-and-bouncing-ray tracing, the ray is

Table Ⅰ. Computation Efficienc Performance with respect to the Number of Scattering Objects.

Data Types		FLOPs VR(100%)	CR+VR	Ratio (%)
4-Face Building	4BDs/ 16 Walls	340	326	95.9
	16BDs/ 64 Walls	1160	820	70.7
	36BDs/ 144 Walls	2460	1482	60.2
6-Face Buildings	4BDS/ 24 Walls	460	380	83.9
	16BDs/ 96 Walls	1640	940	57.3
	36BDs/ 196 Walls	3540	1662	46.9

Table Ⅱ. Computational Efficiency Performance using Hierarchical CR

Order	Avg. FLOPs	Ratio(%)					
VR	8924.1	100	-	-	-	-	
2nd Hier-octree	3610.2	40.45	100	-	-	-	
3rd Hier-octree	2605.3	29.19	72.16	100	-	-	
1st Cr	3672.6	41.15	101.73	-	100	-	
2nd Hier-CR	1805.8	20.24	50.02	69.31	49.17	100	
3rd Hier-CR	1389.7	15.57	38.49	53.34	37.84	76.96	

emitted in all directions with small angular separation ($\alpha = 1^\circ$) with more than 3 reflections considered for each emission. Therefore, it can be assumed that the ray-tracing procedure tests ray-wall intersections at least more than 1,000 times ($= 3 \times 360^\circ/\alpha$). In this simulation, we computed the ray-wall intersection for 100 times. For each computation, the origin and direction of the ray vector is chosen randomly. In Table II and Figure 10, the calculated FLOPS for each hierarchical structure is presented. Compared with the results from VR, both hierarchical octree structures and hierarchical CR show a good reduction ratio of more than 50%. Hierarchical octree structures show the reduction ratio about 60% for 2nd order and about 70% for 3rd order, while hierarchical CR shows more reduction ratio, which is about 80% for 2nd order and about 85% for 3rd order. It should be noted that for the same order of a hierarchical structure, circular representation shows half of the computational loads than octree structures.

3. The efficiency of proposed structures in LOS/NLOS decision problem

As described in Section III, the LOS/NLOS decision is an important problem as well as finding the nearest obstructing wall intersection. All conditions for the simulation are identical as those in simulation 2 and the simulation includes

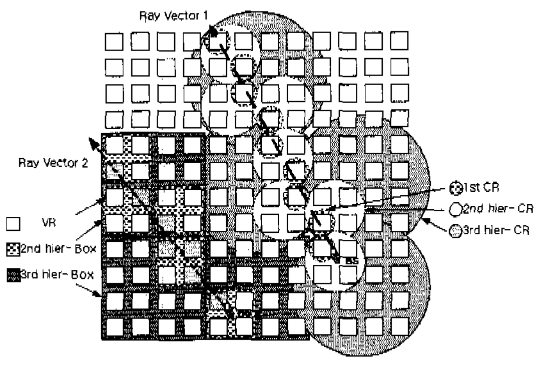

Fig 9. Geometry database for simulation 2

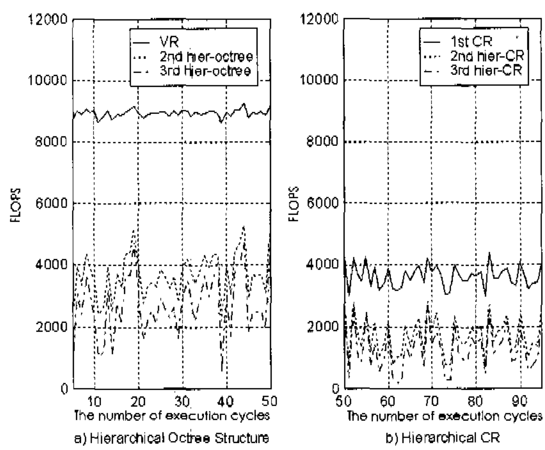

Fig 10. FLOPS Results of hierarchical structure in finding the wall problem

100 computations with different positions and directions. As described in Section III-B, the only difference is whether or not there is a break-out when the ray-wall intersection is found even though it's not the nearest one. Figure 11 and

Table III respectively shows the simulation results. As expected, the computational loads (FLOPS) fluctuate, differing from those shown in Figure 10, because of the presence of random break-out. Average FLOPS are greatly reduced compared to the results of Table II. The results show that circular representation is also more efficient than VR in LOS/NLOS decision problems. As expected, its expansion to hierarchical structure gives more enhancements than hierarchical octree structure.

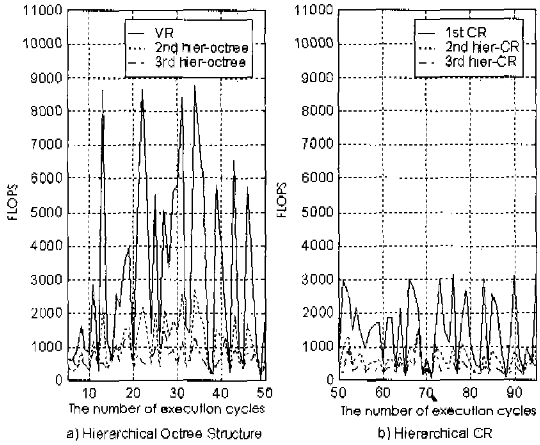

Fig 11. FLOPS results of hierarchical structure in the LOS/NLOS decision problem

Ⅵ. Conclusions

'Circular Representation' of building as additional data structure to VR and constraints with CR to reduce the computational load, which is a critical problem in deterministic model, were presented. For further reduction, a hierarchically structured CR was proposed. Simulations compared reduction ratios between conventional approach with VR and a new approach proposed involving CR format, in the basic problem of finding the nearest wall obstructing the propagating wave. Simulation results showed that computational loads decrease proportionally to the number of scattering objects in the computation. Computational loads with hierarchical CR are found to be only an half of that with a conventional hierarchical octree structure. For one hundred forty-four (144) 12x12 buildings, the proposed approach with CR reduces to about 60% of the computational load compared to a conventional approach with VR. Also, the hierarchical CR reduces to about 80% and 85% for 2nd and 3rd order structure, respectively, while the hierarchical octree reduces to about 60% and 70% for 2nd and 3rd order structure, respectively. The CR data can be stored with VR data or can be generated by a simple pre-processing using Equations (1) and (2) when VR data is loaded. Furthermore, it is expected that when the CR is used with other similar methodologies, more efficiency can be achieved. And for other GIS applications dealing with 2 dimensional building data, the CR also offers further usefulness.

Table Ⅲ. Computational Efficiency Comparison in LOS/NLOS Decision Problem

Order	Avg. FLOPs	Ratio(%)					
VR	3515.9	100	-	-	-	-	
2nd Hier-octree	1197.4	34.06	100	-	-	-	
3rd Hier-octree	762.2	21.68	63.65	100	-	-	
1st Cr	1331.5	37.87	111.2	-	100	-	
2nd Hier-CR	519.45	14.77	43.38	68.15	39.01	100	
3rd Hier-CR	356.52	10.14	29.77	46.78	26.78	68.63	

Ⅶ. Acknowledgments

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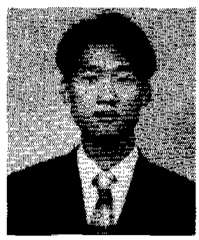

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