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A Propagation Prediction System for Urban Area Macrocells using Ray-tracing Methods

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This article describes the development of UMAP, a propagation prediction system using ray-tracing methods. This system allows to estimate propagation delay time, angle of arrival, radio wave propagation loss etc., by reflecting the influences of actual geography and land features/buildings of a given area in an urban area macrocell environment. By applying the proposed speed-up ray-tracing processing method, this system manages to shorten the time required for computation related to prediction to a great extent.

1. Introduction

Conventionally, the Okumura-Hata model has been used for prediction of radio wave propagation loss for cell designs with macrocell configuration, where the Base Station (BS) antenna is mounted at a location higher than the buildings in the vicinity, and the area is covered by multiple cells with a radius of several km [1]. However, recent cell designs are beginning to require prediction methods that can reflect influences of actual geography and land features/buildings more accurately. Prediction using ray-tracing methods have therefore been actively examined recently, cf. [2] to [5]. Ray-tracing methods are also viewed as a promising approach to evaluation of space-time signal processing technologies in actual propagation environments because they allow predicting propagation delay times and arrival angles of the radio waves in addition to propagation loss [6].

Figure 1 shows an overview of the ray-tracing method used in the prediction system. In the ray-tracing method, all radio waves launched from a transmitter are regarded as rays. First, all rays that finally reach the receiver after undergoing repeated reflection, transmission and diffraction due to buildings in the vicinity are traced geometrically. Next, the electric fields generated by the traced rays are obtained by geometrical optics. In this way, it is possible to predict characteristics of propagation

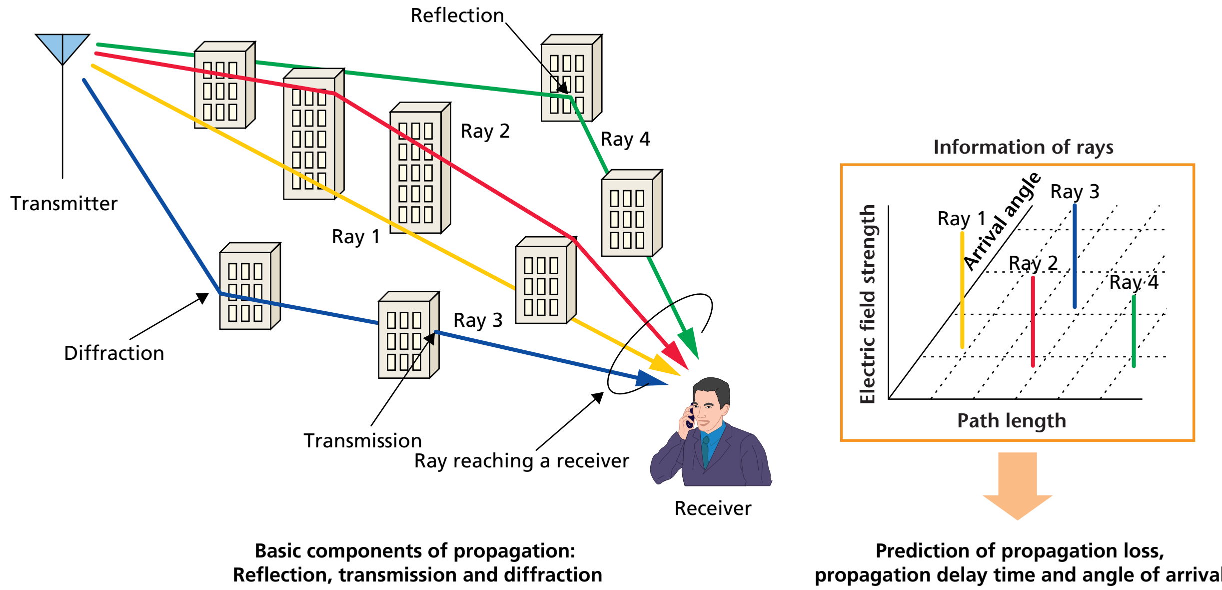

Figure 1 Overview of ray-tracing methods

loss, propagation delay time and angle of arrival, which are necessary for evaluation of mobile communication systems, by using information of propagation distance and incident angle to the receiver of each ray. As explained, ray-tracing is an extremely attractive approach that allows predicting the propagation characteristics relatively easy just by calculating rays between a transmitter and a receiver. The computation throughput, however, is heavily dependent on the number of buildings and the maximum number of times that propagation components are encountered.

In case of urban area macrocell environments, it is necessary to take many buildings in a wide area into consideration in order to predict the propagation sufficiently and accurately with the ray-tracing method. In the conventional approaches, this caused the massive computational load, and a tremendous amount of time was required for prediction if there were many receivers arranged on surfaces, i.e., area prediction. These problems made the method infeasible in practice. In the reference [3], area prediction was achieved within a realistically allowable time frame by using an approximate method. The physical justification for the approximate method is not clear, however, and evaluation of the propagation prediction accuracy is insufficient.

This article first discusses i) the Sighted Objects-based Ray-Tracing (SORT) method ii) the sighted building search algorithm and iii) a novel distributed processing method, which have been proposed to speed up the ray-tracing processing without compromising the prediction accuracy. Next, an overview and the prediction accuracy of the "Urban Macrocell Area Prediction (UMAP)" system will be explained, which is an urban area macrocell propagation prediction system developed based on the above three methods. Note that UMAP only takes the buildings into consideration as structural components. For this reason, in the following discussion, structural components will only be limited to buildings. Moreover, unless otherwise noted, all characteristics related to angle of arrival assume that rays are received at a BS.

2. Speed Enhancement of Ray-tracing Processing

The basic idea of ray-tracing algorithm is tracing the propagation of rays (by means of a path search algorithm) that undergo repeated reflection and transmission between a transmitter and a receiver. In general, the two most frequently used methods are the imaging method and the ray-launching method. The characteristics of each method are briefly discussed below (see [1] for more details).

In the imaging method, a ray is traced by first determining the paths along which the ray propagates by using a given combination of a transmitter, a receiver and possibly one or more wall surfaces, and then searching for reflection points geometrically for each path. In this process, the rays undergoing transmission are also traced at the same time. The main features of this method are i) it is possible to trace all rays which reaches the receiver accurately, ii) the amount of computation processing is almost proportional to the number of paths, which is set beforehand, and iii) the computational load increases roughly proportional to the number of receivers considered in the calculation as well. In this method, many paths will eventually be rejected from the first collection of paths considered, because reflection points cannot be defined on wall surfaces. For this reason, in order to speed up the processing of the imaging method, it is important to select the buildings and wall surfaces to be considered in such a way that the rate of rejected paths be as small as possible. The above points are valid for tracing of rays involving reflection and transmission. In [5], the authors showed that rays involving diffraction can also be traced in the same way.

In the ray-launching method, on the other hand, the launching directions of transmitted rays are determined first, and then the path of each ray is traced geometrically while judging whether an intersection with a wall surface occurs, to obtain the rays reaching the target receiver. When a ray intersects with a wall surface, it is branched into two rays, one in the reflection direction and one in the transmission direction, and each of these is then launched again. The main features of this method are i) since rays are launched in a discretely dispersed manner, it is not possible to trace all rays reaching a receiver in an exact manner, ii) the computational load is roughly proportional to the number of launched rays, which is set beforehand, and iii) the computational load basically does not change even if the number of receivers considered in the calculation increases. There are many preset number of rays launched that may never reach any target receivers, even after undergoing repeated reflection and transmission. For this reason, in order to speed up the processing of the ray-launching method, it is important to select the initial launching directions of the rays to make the rate of rays reaching a receiver as high as possible. The above points are valid for tracing rays involving reflection and transmission. When tracing rays involving diffraction, diffraction points can be regarded as equivalent to new transmitters. In other words, a ray intersecting with a wedge of a wall surface is launched again from the intersection (diffraction point) in multiple directions determined in the same way as for the original transmitter.

As explained so far, the imaging method and the ray-launching method, each have different characteristics and it cannot be said that one approach is consistently better than the other. For conventional prediction in macrocell environments, ray-tracing based on the ray-launching method is the major approach [3], [4] since the number of wall surfaces has little effect on the amount of computational load. UMAP adopts the imaging method as the basis of ray-tracing, however, believing that tracing rays between a transmitter and a receiver in an exact manner is the most important. Note that in macrocell environments in urban areas, the number of buildings that must be considered is extremely large and the path search algorithm will thus require a huge amount of computational processing. In the following, a speed-enhancing method of ray-tracing processing based on the imaging method is therefore proposed.

2.1 SORT Method

Conventionally, many propagation models have been proposed for both prediction and explanation of characteristics of propagation loss, propagation delay time and angle of arrival. Based on studies of these propagation models, the following propagation paths can be said to have significant impacts on each of the propagation characteristics: "propagation paths undergoing multiple-diffraction at rooftops of a building within a vertical plane including a transmitter and receiver" have significant impact on the propagation loss characteristic according to the Walfish-Ikegami model [7], "propagation paths that go through buildings visible from a BS" influence the propagation delay characteristic according to the delay profile prediction model [8] proposed by Takeuchi et al., and "propagation paths that go through buildings within an elliptic scattering area with the road direction as the long axis and the Mobile Station (MS) as the center" as shown in **Figure 2** is important for the angle of arrival characteristic according to the scatter model proposed in [9], [10]. The proposed SORT method is a high-speed ray-tracing method that focuses on these paths.

In the SORT method as shown in Fig.2, rays are traced using buildings visible from a BS and one or more MSs as targets. The procedure is explained below.

1) Search all buildings that are visible from the BS and at least one MS
2) Set the propagation paths of rays using the sighted buildings as targets
3) Trace the rays using the imaging method for each propagation path
4) Identify buildings existing along the traced rays
5) Trace the rays again taking multiple-diffraction caused by the rooftops of the identified buildings into consideration

The SORT method limits the applicable buildings to those buildings in the considered area that are visible from the BS and

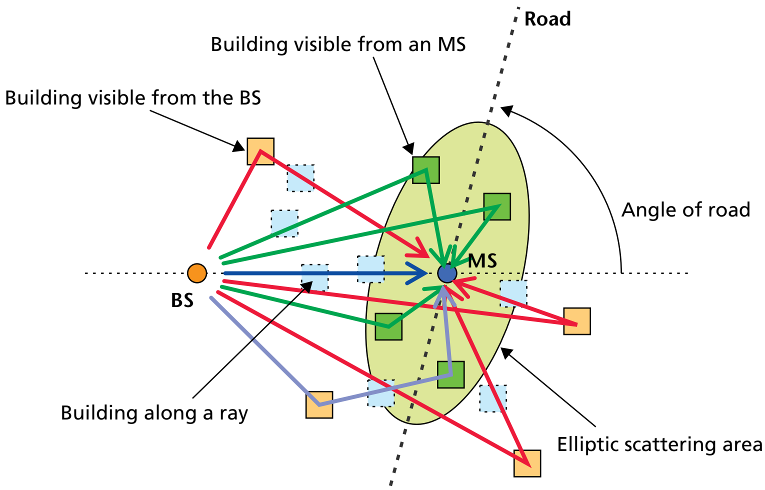

Figure 2 Ray-tracing by the SORT method

at least one MS respectively, and excludes propagation paths that involve "BS→building visible from MS→building visible from BS→MS" from the processing; in this manner, the computation load is significantly reduced. Moreover, all the traced rays are rays that reach a receiver through propagation paths that have significant influence on the propagation characteristics, which means that the deterioration of prediction accuracy due to the limited number of buildings to be taken into consideration is less.

2.2 Sighted Building Search Algorithm

When the SORT method is used, it is necessary to search for all buildings visible from the BS and at least one MS respectively before ray-tracing, and the amount of processing necessary for this step cannot be ignored if the number of buildings to be considered increases.

In ray-tracing in the computer graphics field, one of the major problems has been speed enhancement of judgment of visibility of objects. As one possible solution to this problem, a method for handling objects as a group of multiple objects within a "Bounding Volume (BV)" [11] has been proposed. The authors previously proposed a building search method using a similar method, in order to speed up the indoor ray-tracing processing by the ray-launching method, and evaluated the effects [12], [13]. A sighted building search method using BV is proposed in this article as well. Hereinafter, BVs are referred to as search blocks.

In the proposed sighted building search, the target area considered in the prediction is first divided into search blocks of length ΔL x length ΔL as shown in **Figure 3** . Here, the height ΔH_i of search block i is defined as the height of the highest building in the block. Sighted buildings are searched by the following procedure.

1) Identify the search block j containing the building sighted at the largest angle (in the direction of elevation angle) judged by the observer's point of view, taking the surface height into consideration.
2) Select the highest building m in the detected search block j and create additional lines of sight within both horizontal

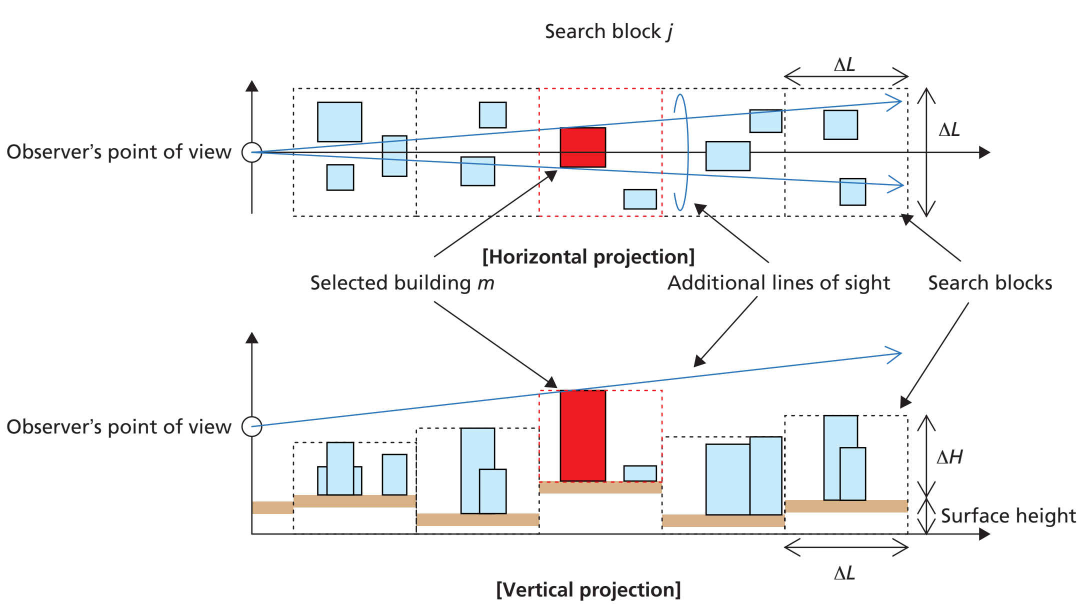

Figure 3 Speed enhancement of sighted building search

and vertical surfaces.

3) Delete all search blocks that are completely hidden from the observer's view by the selected building *m* from the candidates of further search, by tracing the additional lines of sight.
4) Re-build the list of buildings in other search blocks *k* that are not completely hidden from the observer's view by the selected building *m*, deleting hidden buildings from the search candidates. Modify the height ΔH_k of the search blocks as necessary.
5) Save the selected building *m* in a database as a sighted building and delete it from search block *j*. Modify the height ΔH_j using the remaining buildings.

By repeating steps 1) through 5) until there are no more sighted building candidates, all the buildings visible from the observer's point of view can eventually be obtained. This method allows deleting multiple hidden buildings at once, which speeds up the processing.

2.3 Distribution Processing Method

Whether the imaging method or the ray-launching method is used, the ray-tracing processing involves sequential operations and can easily be distributed. In the following, the distributed processing method of ray-tracing operations is explained, assuming that the proposed SORT method and sighted building search algorithm are to be used.

As shown in **Figure 4**, the proposed ray-tracing operations can largely be divided into seven processing steps. Distribution processing of the operations is possible in each of the steps. However, if data has to be communicated frequently between the computers executing distributed processing, it is highly likely that the data transfer speed becomes a bottleneck in the distributed processing. For this reason, rather than performing distributed processing in each step, the proposed method uses distribution processing step #3 by putting the execution of the SORT method and the computation of the electric fields generated by the rays together in one step, as also shown in Fig.4. The unit of operations in each of the distributed processing steps #1 through #3 is explained in the following.

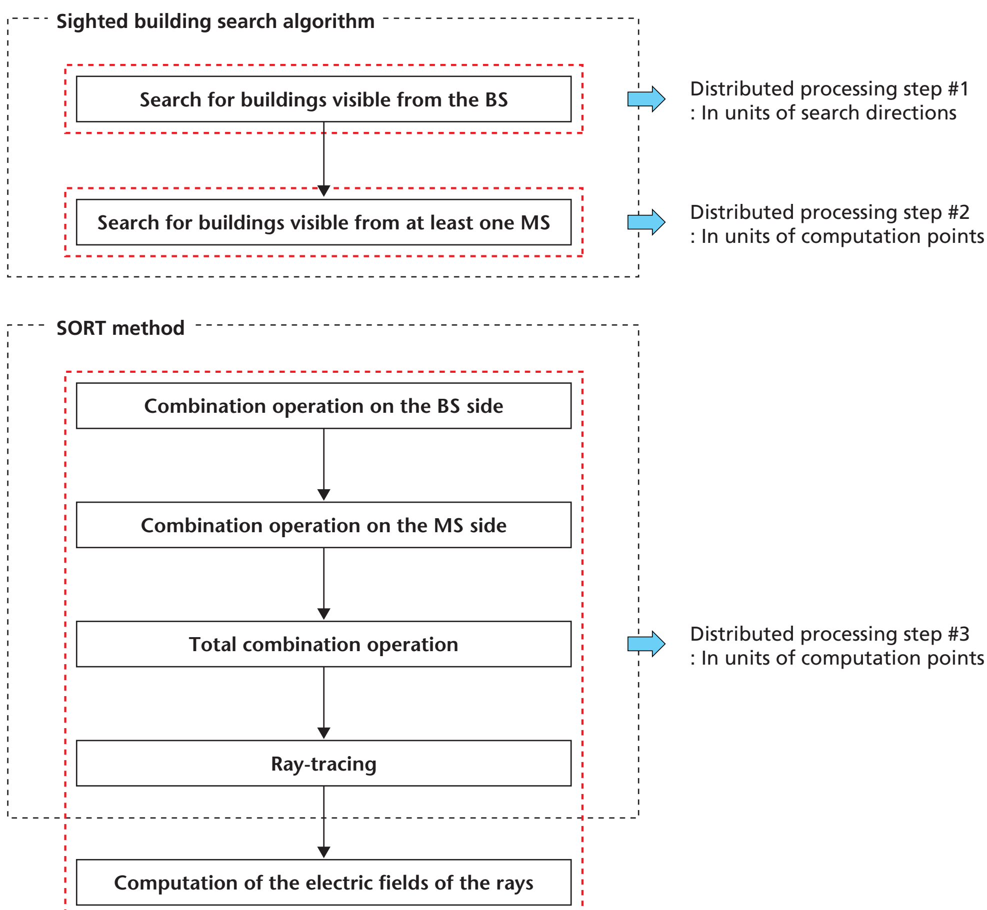

Figure 4 Processing flow and distribution of ray-tracing

In case of macrocell environments where the BS antenna is higher than any of the buildings in the vicinity, there are many buildings that will be visible from the BS. For this reason, in distributed processing step #1, an area corresponding to the angle obtained by dividing the 360° of the horizontal plane by the number of computers to be used for the computation processing is set as the basic unit of distribution. Furthermore, when performing area prediction, an extremely large number of computation points (MS positions) may become the computation targets. For this reason, in distribution processing steps #2 and #3, an area obtained by dividing the prediction area by the number of computers is used as the basic unit of distribution. Note that, in the developed UMAP system, the maximum number of computers per BS that can be assigned processing tasks is four in distribution processing step #1 in order to simplify the distribution control. Moreover, in distribution processing steps #2 and #3, the size of the area (the number of computation points) to be distributed to a given computer can be adjusted by taking the processing speed of the computer into consideration.

Above is the proposed speed-up method of ray-tracing processing. These methods can be classified according to the technology used as follows: the SORT method reduces the amount of computation processing required, the sighted building search algorithm speeds up computation by software/algorithmic means, and the distribution processing method is an approach to achieve high-speed computation by hardware means. This also means that there is no degration of prediction accuracy in using the proposed sighted building algorithm and the distributed processing.

3. Propagation Prediction System UMAP

3.1 System Configuration and Functional Structure

Figure 5 shows the system configuration and functional structure of UMAP. UMAP consists of clients equipped with all the propagation prediction functions based on the ray-tracing method, and distributed servers, which are only equipped with analysis processing functions. Windows 2000 is used as the basic operating system on the client side, where the users' control operations are handled, and a UNIX OS (e.g., IRIX, Linux etc.) is used for the distributed server that handles processing operations only. Note that performing computations on the client machines alone is also possible, and the distributed server is not always necessary. The maximum number of distributed servers and the maximum number of Central Processing Units (CPUs) per distributed server that can be connected are both 32. The operation of the system was actually tested on a network

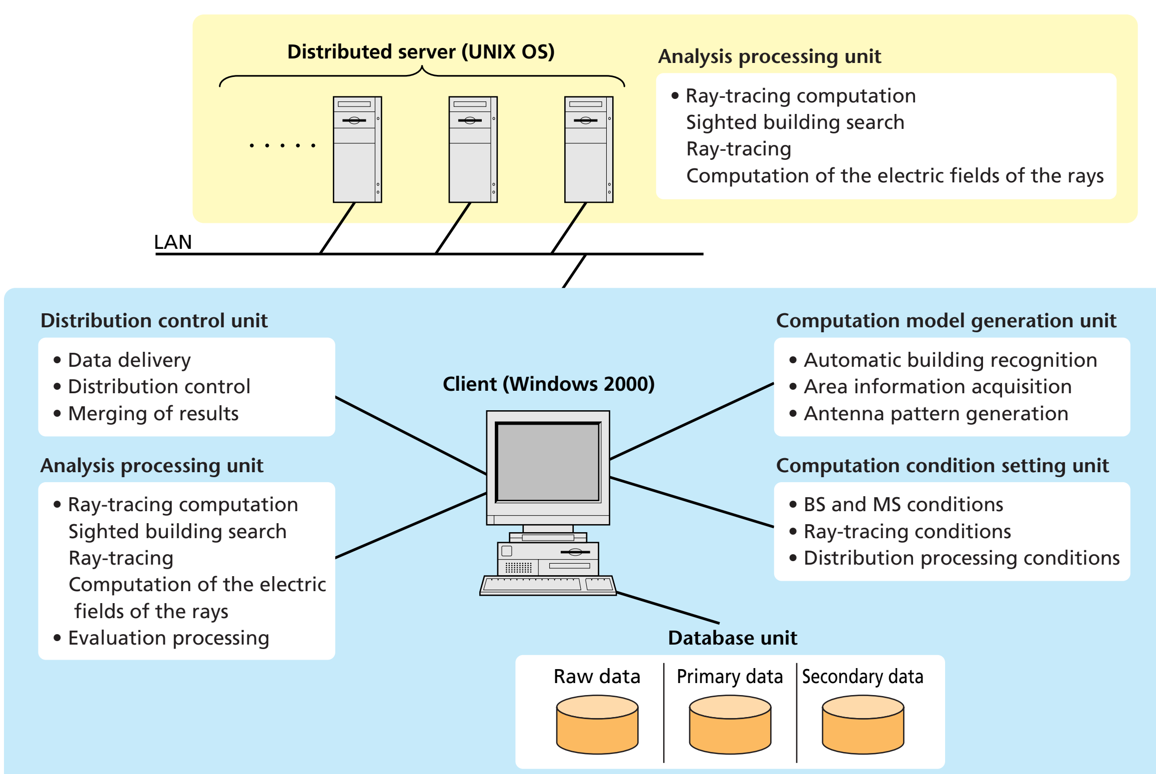

Figure 5 System configuration and functional structure

with a total of 13 computers connected simultaneously (with a total of 52 CPUs): 1 SGI_Origin 3800 (equipped with 32 units of 350 MHz RISC processor CPUs), 8 PCs (equipped with 2 units of 3.2 GHz Pentium 4 CPUs), 1 PC (equipped with 1 unit of 2 GHz Pentium 4 CPU) and 3 PCs (equipped with 1 unit of 933 MHz Pentium III CPU).

The overall functions of UMAP consist of the "database unit," "computation model generation unit," "computation condition setting unit," "distribution control unit" and "analysis processing unit." Each of the functions is briefly explained below.

1) Database Unit

The database unit manages raw model data consisting of geographical data and building data, primary data consisting of building data and area information data for ray-tracing created in the computation model generation unit and antenna pattern data, and secondary data consisting of data of buildings visible from the BS and at least one MS respectively, obtained in the analysis processing unit and ray-tracing computation result.

2) Computation Model Generation Unit

The computation model generation unit creates various types of primary data that is used in the ray-tracing computation. The main functions are as follow.

The automatic building recognition function uses commercially available house maps (raw building data) to automatically recognize the position (latitude and longitude), height and two-dimensional shape of a building, and create building data for ray-tracing by attaching electrical characteristics (relative permittivity, relative permeability and conductivity) set by the user to the house objects.

In the area information acquisition, the predicted area is first divided into search blocks and basic meshes as shown in **Figure 6**. Search block information (block ID, block height, surface height, building IDs included etc.) and mesh information (mesh ID, search block IDs included, mesh height, mesh attributes: with/without buildings etc.) is then obtained from the raw geographical data and building data to be used in the ray-tracing as area information. All the information is placed in the database. Note that the default size of search block is 100 m x 100 m, and the size of the basic mesh is 10 m x 10 m.

3) Computation Condition Setting Unit

The computation condition setting unit handles the setting of BS conditions, MS conditions, ray-tracing conditions and distributed processing conditions that are necessary for propagation prediction using the ray-tracing method.

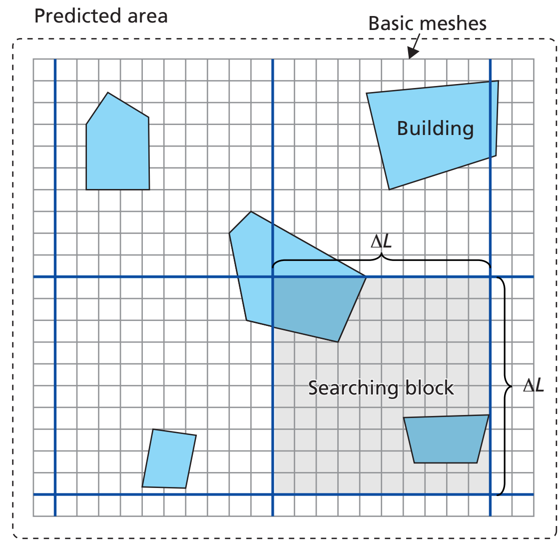

Figure 6 Dividing predicted area into meshes and blocks

The main items to be set as BS conditions include the position (latitude and longitude) and height, transmission power, transmission/reception frequency and type of BS antenna. The main items to be set as MS conditions include the position (latitude and longitude) and height of MS (calculation point) and type of MS antenna.

The ray-tracing conditions include the maximum number of reflections and diffractions when rays intersect with building surfaces visible from the BS side (maximum number of times on the BS side), the maximum number of reflections and diffractions when rays intersect with building surfaces visible from the MS side (maximum number of times on the MS side), and the ultimate maximum number of reflections and diffractions of rays to be traced (maximum total number of times). Moreover, in order to limit the number of visible buildings obtained when searching through the buildings during the ray-tracing, the minimum building height on the BS and MS sides can also be entered. With this function, all buildings lower than the minimum building height on the BS (or MS) side are excluded from the targets of ray-tracing.

The distributed processing conditions describe the Internet Protocol (IP) addresses of computers (distributed servers) used for distributed processing and the performance ratio among the computers. The performance ratio is a value set by the user taking the computation speed of the individual computers into consideration. The size of the computation area (number of computation points) each computer will be in charge of is determined based on this value.

Although it is not listed in Fig.5, there are a few other conditions that can be set; for instance it is also possible to set the maximum search distance for visible buildings from the BS and MS sides, respectively.

4) Distribution Control Unit

The distribution control unit controls data communication and the timing between clients and distributed server, and monitors the progress of the computation processing at each distributed server at fixed intervals.

5) Analysis Processing Unit

The analysis processing unit performs the ray-tracing computation using the proposed methods, and displays the results. The main items displayed include calculation information (e.g., the time it took to perform the calculation), result of searching for visible buildings, result of ray-tracing, delay profile, profile of angle of arrival on the BS side and profile of angle of arrival on the MS side. Moreover, for evaluation of the propagation characteristics, the reception power, propagation loss, delay spread and angle spread are calculated for each computation point.

3.2 System Performance

This section presents the prediction performance of UMAP in an actual propagation environment model. The chosen target area is Aoyama in Tokyo, and the prediction was performed under the following conditions: frequency: 2.2 GHz, transmission power: 35 dBm, BS antenna height: 60 m, MS antenna height: 3.5 m. Here, both the BS and MS antennas are hypothesized as being ideal antennas (omnidirectional, with a gain of 0 dBi). Moreover, the following ray-tracing conditions are set: maximum total number of reflections: 1 (BS side: 1, or MS side: 1), maximum total number of diffractions: 1 (BS side: 1, or MS side: 1), minimum building height on the BS side: 60 m (the same as the BS antenna height), and minimum building height on the MS side: 0 m (the surface height). Other conditions include that all buildings are assumed to be made of concrete (relative permittivity: 6.76, relative permeability: 1, conductivity: 0.0023 S/m) and the maximum distance to search for visible buildings is set to 1 km for both the BS and MS sides. The prediction results obtained by computation are shown below.

1) Ray-tracing

The starting point of the proposed ray-tracing algorithm is searching for buildings visible from the BS and at least one MS respectively. **Figure 7** shows an example of ray-tracing results together with the result of searching for visible buildings. It can be seen that many more buildings are visible from the BS side (displayed in blue green color) than from the MS side (displayed in yellow green color), and that the buildings visible from the MS side are mainly located along the roadside where the MS is located. This is due to the fact that the average height of buildings in the vicinity of the MS positions is approximately 20 m. The targets of the ray-tracing computation are those buildings among the buildings visible from the BS and an MS respectively matching the condition of the minimum building height explained above; they are shown in orange in the figure displaying “rays between BS and MS.” Note that the color of each ray indicates the reception power of that particular ray. The

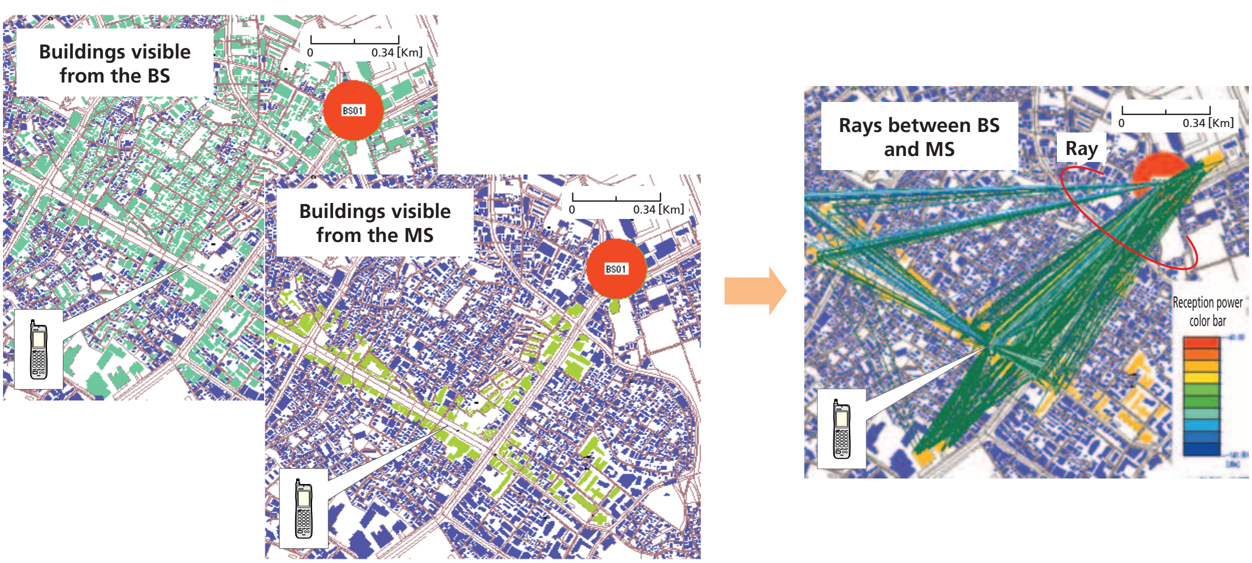

Figure 7 Result examples of ray-tracing

power levels corresponding to the different colors are displayed in the color bar attached to the same figure. From these results, it is understood that the proposed sighted building search algorithm and SORT method are performed in UMAP as expected.

In the computation example in Fig.7, prediction was executed using a client PC (1 unit of 2 GHz Pentium 4 CPU) only without performing distributed processing. The time required for the computation was approximately one minute.

2) Area Prediction for Propagation Characteristics

Figure 8 shows an example of results where prediction was performed for an area of 1 km x 1 km, in which the BS was situated. Note that each MS is located in the center of each 10 m mesh and the number of meshes is 11,188 (not including meshes covered by buildings). From these results, the reception power, delay spread and angle spread within the area can clearly be seen. For example, the reception power tends to become large on roads that are lined up with the BS, at intersections and in open spaces.

This computation example was performed using 1 SGI_Origin3800 (32 units of 350 MHz RISC processor CPUs) and 1 PC (1 unit of 2 GHz Pentium 4 CPU). The time required for the computation was approximately 53 hours.

4. Comparison with Actual Measurement Result

To test the accuracy of the system, the prediction results were compared with actual measurement results of MS transmission/fixed point measurements (time-space path data) in Aoyama, Tokyo, which has already been reported in the reference [9] and [10]. A 16-element linear array antenna (8.3 dBi, half-power bandwidth within horizontal surface 120°) and a sleeve antenna (gain 2.2 dBi) were used for the BS and MS antennas, respectively; all other BS and MS conditions are the same as the settings in Section 3.2. Moreover, radio waves were transmitted at 117 different MS positions; all these points are on roads invisible from the BS within the predicted area, as shown in Fig.8.

In the UMAP prediction, MS positions (computation points) were set at the same positions as the measurement and ray-tracing was performed for each calculation point. The same antennas as used in the measurement were set for the BS and MS antennas, and all other conditions were set to the same values as described in Section 3.2.

Figure 9 shows the comparison between the actual measurement and predicted result. Note that the predicted value of reception power is defined as power summation of rays in order to eliminate the effects of phase difference of each ray. Fig.9(a) shows the actual measurement values and predicted values, together with the logarithmic regression results as well as prediction according to the Okumura-Hata model. From these figures, it is understood that the predicted values and the actual measurement values match relatively well. The prediction errors were, in cumulative 50% values, as follows: reception power: 6 dB, delay spread: 0.2 μsec, angle spread: 3°. Moreover, the average values of the 117 points were as follows: reception power: –79 (±13) dBm for the predicted values and –82 (±11) dBm for the actual measurement values, delay spread: 0.33 (±0.33) μsec for the predicted values and 0.52 (±0.45) μsec for

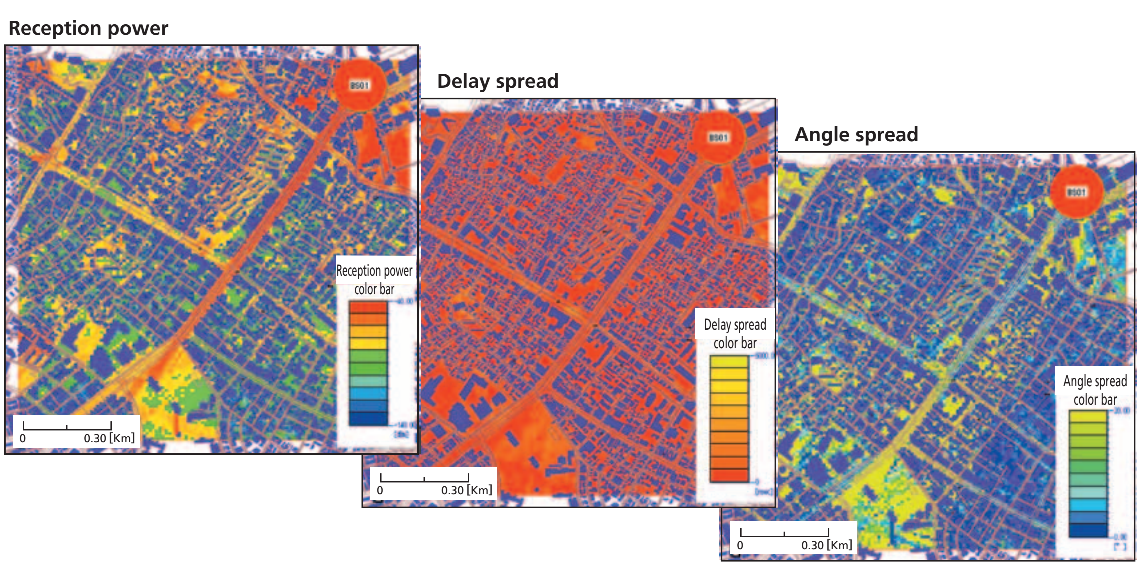

Figure 8 Examples of propagation prediction results

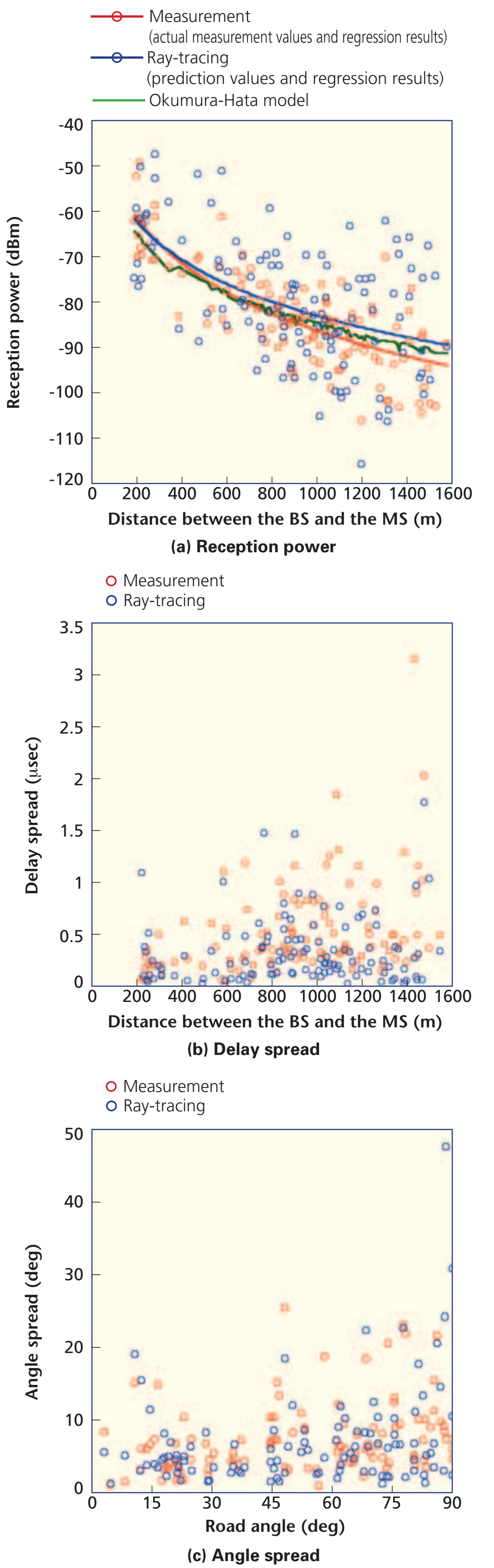

Figure 9 Comparison with actual measurement results

the actual measurement values, and angle spread: 5.48 (±6.0)° for the predicted values and 6.72 (±5.5)° μsec for the actual measurement values. The values in parentheses are standard deviations.

Incidentally, the causes of prediction errors include inaccuracies in the MS positions and inaccuracies in the building data (position, shape and height), and they tend to become prominent in fixed-point evaluations such as in this case. For this reason, averaged values such as those for short intervals of several ten meters should normally be assumed for evaluation; in such cases, the prediction errors can be expected to be less.

5. Conclusion

This article presented UMAP, a ray-tracing-based propagation prediction system, which allows predicting not only radio wave propagation loss, but also characteristics such as propagation delay time and angle of arrival in urban area macrocell environments. Conventionally, a massive computation processing was required to predict urban area macrocell environment accurately using ray-tracing methods, and it was difficult to build a practical area prediction system. UMAP, using the proposed SORT method, sighted building search algorithm and distributed processing method, dramatically shortens the processing time without losing prediction accuracy and allows processing in real-time. Moreover, this article showed that UMAP can predict the reception power (propagation loss characteristic), delay spread (propagation delay characteristics) and angle spread (characteristic of angle of arrival) accurately, by comparing the prediction results with the actual measurement results in Tokyo in the 2.2 GHz band.

A future issue will be to compare with more measurement results to improve the reliability of UMAP and develop it into a next-generation cell design tool.

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ABBREVIATIONS

BS: Base Station
BV: Bounding Volume
CPU: Central Processing Unit
IP: Internet Protocol
LAN: Local Area Network
MS: Mobile Station
SORT: Sighted Objects based Ray-Tracing method
UMAP: Urban Macrocell Area Prediction System