Matrix Based Ray-tracing Model for Indoor Propagation

Damir Zrno, Dina Šimunić
Department of Radiocommunications and Microwave Engineering
Faculty of Electrical Engineering and Computing
Unska 3, 10000 Zagreb, Croatia
Phone: +385-91-42-42-426 E-mail: damir.zrno@fer.hr

***Abstract* – This paper presents a fast and accurate method for indoor signal strength prediction. Method is based on pathloss pre-calculation for the whole coverage area of an access point in free space. Resulting matrix and object masks are used to calculate signal strength for all points simultaneously minimizing the number of needed calculations and reducing prediction time significantly. Also discussed is the upgrade to 3D prediction.**

Keywords* – *indoor wireless communications, path loss calculation, ray tracing, 2D, 3D

I. INTRODUCTION

With the growth of the indoor wireless market, it becomes ever more important to have an efficient way of predicting in-building radio propagation, thus reducing the number of needed base stations and providing a better coverage. With the increase of customers that want to implement indoor wireless, there is a great need for a fast and accurate prediction model that would enable quick network planning.

Due to a large number of objects and walls in indoor environments, many paths of propagation reach the receiving point. Materials and layout of the building and its walls have a large impact on multipath propagation. Methods required to calculate indoor pathloss are therefore much more complex than those used for outdoor calculation.

There are several approaches when predicting radio propagation. The simple one is to calculate pathloss the same way it is done for outdoor environment – by taking the free-space equation and adding correction factors and changing the loss exponent to best simulate the given environment [1], [2]. This method is fairly fast, and it gives only the order of magnitude.

Approach that we are using is ray tracing modeling. This means predicting the propagation for each of the multiple paths that are received by the mobile equipment. As the received rays are numerous in the indoor environment, and accompanied by multiple reflections, transmissions, diffractions, applying this method fully would take a colosal amount of time and resources for prediction. This article presents a faster method of calculation based on matrix manipulation, and focuses on propagation prediction above 2 GHz.

II. PROPAGATION PHENOMENA

Standard ray tracing models predict coverage on a point by point basis. They predict the signal strength and phase of each ray that reaches the receiver taking a huge amount of time for calculation [3]. This is redundant as only several objects affect propagation in the area of a single access point, which means that a lot of map pixels share the same phenomena associated with same objects.

Instead of calculating everything for each map point, it would be faster and more efficient to determine the groups of rays that encounter the same propagation phenomena and calculate them all simultaneously, as this would save a lot of calculation time.

The idea presented here bases calculation on matrix manipulation. The goal is to reduce the number of mathematical calculations, as well as hastening the propagation prediction by using pre-calculated pathloss matrices.

Each access point used in indoor propagation has a maximum range of coverage in free space, and slightly larger area has to be observed to take into account the possibility of waveguiding.

The indoor environment changes constantly as doors are opened and closed and as people move around or move the furniture. Taking a high map resolution would not improve results, as all objects in a room can't possibly be taken into account. If a resolution of 0.5 meters is used with 50 meters maximum range, only 100 values need to be pre-calculated (one for each 0.5 meters in range) for free-space pathloss. All values in between are rounded to them. This brings a certain error into the calculation, but the maximum error at 20 meters distance is about 2,5% in absolute signal strength, or 0.1dB in relative strength. That value is well within standard deviation for indoor prediction models. The benefit is that whenever free space signal strength at some point is needed we only need to refer to the closest calculated value.

Next improvement comes from the nature of wave propagation [4-5]. Let's assume that there are no walls or objects in the coverage area of any AP. Instead of calculating the pathloss for all of them, it only needs to be done once for the whole area within 50m of one access point, and that result can be used for calculation of all other APs. Only the transmission power of each access point is needed to complete the coverage calculation. In this ideal case only one 200x200 matrix (50m on each side of the AP) is used providing an improvement in calculation time. If that matrix is obtained using the pre-calculated values, the process is simply shortened to finding 40,000 distances, copying appropriate values to the final matrix and applying the final matrix to each of the APs. Distances can also be precalculated to reduce the calculation speed further. Compared to the standard method that would calculate the free space loss 40,000 times for each AP, this method is undoubtedly much faster.

This was only the free-space case and all propagation phenomena need to be taken into account in order to gain a complete and accurate prediction model. Scattering will intentionally be omited in indoor environment. Its strength level is usually so low compared to other rays that it can be overlooked without a significant calculation error.

A. Transmission

Transmission is used in all indoor propagation prediction tools as it provides the biggest part of signal strength in cases when there is no direct line of sight [6]. It is rather easy to implement, as it only requires checking if an object stands on the ray path or not. If so, then the intersection is determined and additional transmission loss is added. This loss depends on the wall material and thickness.

Instead of calculating the transmission loss for every ray, it would be easier to determine the group of rays that pass through the wall and add the loss to all those rays. In order to do that, we need the information on the position of the wall and on its parameters (thickness, materials), as well as the position of the access point.

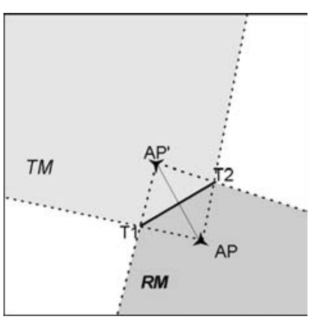

Fig.1. Transmission and reflection areas

In the case of a single object, transmission loss is added to the pre-calculated free-space matrix in the area masked by the object. In order to find the mask we need to find the edge lines that touch the wall edges, and then we need to create a mask from the wall and those lines – again a matrix. Next, mask should be multiplied with the transmission loss (in dB) and added to the original free-space pathloss matrix.

Matrix operations take the largest amount of time in this process, but only three were required:

- Creation of a matrix (mask)
- Multiplication (by a constant)
- Matrix addition

When compared to 40,000 logarithmic equations and the search for several thousands intersections, the proposed solution gives an enormous decrease of calculation time.

B. Reflection

Pathloss calculation also involves a lot of reflected rays. Existing models calculate transmissions and reflections based on the incident ray and repeat the process for all observed rays. All of these rays have the same point of origin and follow the same rules in reflection. They behave the same way as light falling on semi-transparent material, meaning that we can apply basic principles of optic geometry so that reflected rays can be observed as transmission from a mirrored access point. Instead of calculating reflection for each ray, only the mirrored image of the access point needs to be found and all the reflected rays can be calculated as if they were direct path rays (Fig.1.).

This gives a great improvement in calculation time in matrix based propagation model. Only the coordinates of the original access point and the coordinates of the wall edges are needed, and the image of the access point (AP’) and the area shadowed by the wall can easily be calculated from them. After that reflection can be treated the same way as transmission, the only difference is that reflection losses are used instead of transmission losses in signal strength prediction.

Reflection losses can be calculated using the reflection coefficient of the ray perpendicular to the wall by adding that value to each the reflected ray area. This brings an error in reflection calculation that is dependent on the incident angle. The other option is to use the reflection coefficient for each used wall type depending on the incident angle, wave polarization and frequency. These values should be written in a reflection coefficient matrix for each wall material used. When reflection from a wall is calculated, this matrix is rotated and multiplied by wall mask. This way we have created a mask that has reflection coefficients written in all pixels affected by reflection. Incident signal matrix also has to be rotated and mirrored to find the signal strength for the mirrored AP'. By adding reflection coefficient mask to the mirrored signal matrix the reflected ray matrix is obtained.

Reflected rays are nothing more than additional signal components in multipath propagation. Once we have the reflected ray pathloss matrix and the direct ray pathloss matrix, we can combine them to make a single pathloss matrix as they represent two rays that reach the receiver.

C. Diffraction

Calculations of reflection and transmission are enough in most cases (diffraction can be omitted for the 6 GHz frequency range), but sometimes the diffracted rays carry a large part of signal strength for an area. This is especially the case in areas only slightly shadowed by walls (close to the direct ray between transmitter and receiver), or in areas shadowed by walls with high absorption.

Several parameters are important for matrix based diffraction calculation – the distance between the access point and the wall edge where diffraction occurs (important for free-space pathloss calculation), frequency and the angle between the diffracting ray and the wall.

The wall edge where the diffraction occurs can be viewed as a new source and a new matrix needs to be made that will represent another multipath component. This matrix will be centered at the wall edge and it will have a distance offset, and the diffracted signal strength has to be calculated point by point for each pixel of the diffraction matrix. Two important factors are the angle of the diffracted ray to the initial ray, and the distance to the receiver. This matrix is then used to obtain the real pathloss for all points in the shadowed area.

In the overall view, the areas on which the diffraction has a significant impact cover only a small portion of the total coverage area. If the walls have low absorption (under a few dB) and are letting most of the signal through, then the diffracted rays provide a negligible part of the strength (typical wall losses in concrete and brick buildings are around 13 dB in the 2 GHz frequency range and typical knife edge losses are 20-30 dB). A possible improvement in calculation speed would be to pre-calculate the diffraction matrix for one distance of transmitter and the wall edge, and then scale that matrix for different distances. The downpoint is the change in resolution that comes from scaling.

III. CALCULATING COMPLEX ENVIRONMENTS

So far, only the cases with one object in the coverage area have been considered. Prediction of indoor propagation in a real indoor environment is much more complex as it includes numerous objects. The solution to this problem in matrix-based calculations is similar to the techniques used in ray tracing. For instance when calculating transmission behind a wall, a check has to be made to see if there are any other objects in the calculated area. In effect this requires an object tree for calculations. This object tree need not be made at the start and can be created 'on the fly' by searching areas with sufficient signal strength for objects. This avoids search for visibility relations between all objects.

The procedure is based on recursion - each time a new mask is created, a search should determine if there is an object within the mask area. If so, a new sub-branch in the current object branch is opened and its masks found (Fig.2. and Fig.3.). This process repeats until we find a mask area that has no objects within its area (masks get smaller as we go further down the object tree due to pathloss limitations on range). Once we reach such a mask, we calculate the pathloss for that sub-branch and move on to the next sub-branch one step up the tree. Once all sub-branches have been calculated they are combined as multipath signals. This ends once all the main branches (direct ray objects) have been processed.

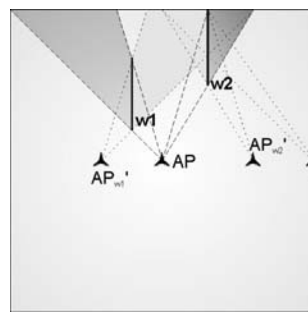

Fig.2. Calculation example with two walls in coverage area

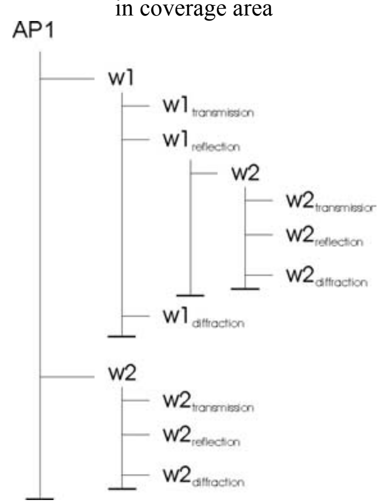

Fig.3. Object tree for figure 2

Calculation time for a single AP depends only on the maximum coverage range and on the number of objects within. If the environment has large absorption coefficients for objects within, it will take less time for calculation, as the masks will be smaller due to lower signal strength.

There is another important aspect in pathloss calculation and that is the influence of the floor reflected ray and the ceiling reflected ray. This is a wave guiding effect, and should be taken into account right in the first pre-calculation for the free-space matrix, although this means that the same receiver height is presumed for the whole area. It is assumed that the floor and the ceiling are not slanted, which makes this basically a single-floor model. Propagation through floors is much more difficult because of the thickness of floors and the iron grid within. This provides significant signal attenuation between floors and any would-be interference between the floors can be avoided by careful channel planning.

A more complex environment calculation is shown in Fig.4. These results were obtained from software based on matrix calculation that we developed. Dimensions of the test environment were 20x20 meters, the resolution was 5 centimeters, and transmission and reflection signals were considered. The final matrix contained results for 160,801 points and took 218 seconds to calculate, which is considerably lower from traditional ray-tracing methods.

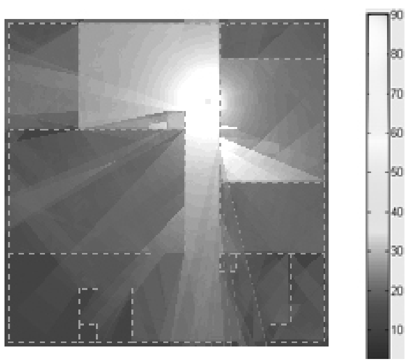

Fig.4. Calculation results for prediction using matrix based calculation

IV. UPGRADING FROM 2D TO 3D

So far we have discussed prediction for 2D model, but matrix calculation can also be used for 3D calculations. The first step would be to add the third dimension to signal matrix. Instead of pre-calculating free space loss for a single height of a receiver, the whole procedure would first be applied to the area between the ceiling and the floor which would result in a matrix showing signal strength depending on the receiver height and distance from the base station. Instead of using single values for signal strength at each map pixel, this would give a whole array of values for different heights. The model we used presumes same floor and ceiling height on the whole map area, and absence of any sloped walls (which is usually the case).

If a full 3D model is desired, the same principles can be used, but the matrices become much larger as a third dimension is added and used for calculations. If the original matrices were 200 pixels on the side, the calculations will be that much longer. This is obviously a huge increase in calculation time, but it can partially be avoided by reducing the size of matrices on each tree sub-level. If the object is at half the maximum distance, the whole matrix can be reduced eight times due to the lower signal strength. Taking into account transmission and reflection losses reduces this even further.

V. CONCLUSION

The matrix-based model presented in this article offers a different approach to the indoor propagation prediction from standard ray-tracing models. It avoids most of the calculations usually performed in those models and uses only basic mathematical operations on matrices to speed up the calculations. As discussed before, this brings a great improvement in calculation time. Calculation time and complexity depend mostly on the maximum calculation range, and if the range is increased only by a factor of two, this may increase the calculation time tenfold. This model is therefore best suited for indoor calculations where the range is fairly small, and for frequencies above 5 GHz.

REFERENCES

[1] R. Hoppe, P. Wertz, G. Wölfle, and F. M. Landstorfer, “Wideband Propagation Modelling for Indoor Environments and for Radio Transmission into Buildings“, *PIMRC 2000, The 11th IEEE International Symposium on Personal, Indoor and Mobile Radio Communication, London (UK), 18-21 September 2000*

[2] E.Pop, V.Croitoru, R. Antohi, “Site Engineering for Indoor Wireless Spread Spectrum Communicationsc, *The 8^{th} IEEE International Conference on Telecommunications, Romania, Bucharest, 4-7^{th} June, 2001*

[3] J. Zhong, “Efficient Ray-Tracing Methods for Propagation Prediction for Indoor Wireless Communications”

[4] D. Šimunić, "Mikrovalne komunikacije", skripta, FER, 2001

[5] E. Zentner, “Radiokomunikacije”, *Školska knjiga, Zagreb, 1989.*

[6] J.H. Tarng, W.R.Chang, and B.J.Hsu, “Three-Dimensional Modelling of 900-MHz and 2.44-GHz Radio Propagation in Corridors”, *IEEE Transactions on Vehicular Technology, vol. 46, no.2, May 1997*