Efficient and Accurate Urban Outdoor Radio Wave Propagation

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***Abstract*—Simulating Radio Wave Propagation using geometrical optics is a well known method. We introduce and compare a simplified 2D beam tracing and a very general 3D ray tracing approach, called photon path tracing. Both methods are designed for outdoor, urban scenarios. The 2D approach is computationally less expensive and can still model an important part of propagation effects. The 3D approach is more general, and not limited to outdoor scenarios, and does not impose constraints or assumptions on the scene geometry. We develop methods to adapt the simulation parameters to real measurements and compare the accuracy of both presented algorithms.**

I. Introduction

There are different approaches to solving the problem of simulating radio wave propagation. In this work we concentrate on deterministic approaches, that use geometrical optics. This leads to algorithms using ray tracing and beam tracing. Both techniques model radio waves as individual particles or bundles of particles traveling along straight lines. Reflection and transmission of plane waves can be modeled very well by this. This theory can also be extended to capture more complex behavior of radio waves, such as diffraction. All three optical effects are important to correctly model all dominant propagation paths in urban outdoor environments. Especially reflection off building walls and diffraction at roof tops or building corners are essential for an accurate simulation. Computing all important propagation paths allows us to predict average signal strength and delay spread characteristics at arbitrary points in the scene.

There is a distinction between ray tracing and beam tracing algorithms. The latter can be more efficient, because they trace a bundle of rays concurrently. On the other hand beam tracing algorithms tend to be more complex than ray tracing algorithms, especially when dealing with full 3D simulations. Hence we only implement a 2D beam tracing approach and compare it with a 3D ray tracing algorithm. The beam tracing method uses building heights as an additional information, which we call a 2.5D representation of the data. This leads to a simple and fast algorithm with acceptable accuracy. The 3D ray tracer is more general, but also not as fast as the beam tracing method.

II. Related Work

A good overview of radio wave propagation models is given in the COST 273 report [1]. Usually one distinguishes between stochastic (empirical) channel models and deterministic propagation algorithms. The best known examples of empirical models are the work of Hata [2] and Ikegami [3]. They use parameterized functions for approximating the propagation loss. Hata conducted extensive measurement campaigns, whereas Ikegami extended Hata's work. He analyzed the dependence of the equations with respect to height gain, street width, propagation distance and radio frequency. These empirical models have the advantage of short evaluation time but are prone to prediction errors and perform especially poor in heterogeneous propagation environments like historically grown cities [4].

On the other hand, deterministic algorithms for predicting radio signal strength compute propagation paths due to physical effects like reflection, diffraction and scattering. Ray tracing was proved to be a good technique for estimating propagation losses by Ikegami [5]. Other authors using ray tracing, like Schaubach [6], Schmitz [7], and Kim [8], found predicted path loss values to be within 4 to 8 dB of the measured path loss. Such predictions are considered to be of very high accuracy.

Instead of tracing single rays, beam tracing takes a continuum of rays. This method was introduced by Heckbert and Hanrahan [9]. This alleviates sampling problems and helps reducing intersection tests. Beam tracing has been used for both real-time rendering [10] as well as audio simulations [11].

We employ ray and beam tracing for radio wave propagation. By implementing the beam tracing on the GPU we get a propagation prediction with both high accuracy and in a speed that has not been achieved before. Similar to our beam tracing approach is the work by Rajkumar et al. [12]. Moreover Fortune presented a beam tracing approach for indoor wave propagation [13].

Furthermore, Rick et. al. presented a GPU-based approach to radio wave propagation in Catrein [14] and Rick [15]. They trace propagation paths in a discrete fashion by repeated rasterization of line-of-sight regions. However, since only the mean received signal strength is computed, multi-path effects, which are an essential requirement for delay spread estimations, are completely neglected. This is not the case with our algorithms. Besides basic propagation losses, advanced channel characteristics like the delay spread are computed. However, in this work we will concentrate on the path loss computation only.

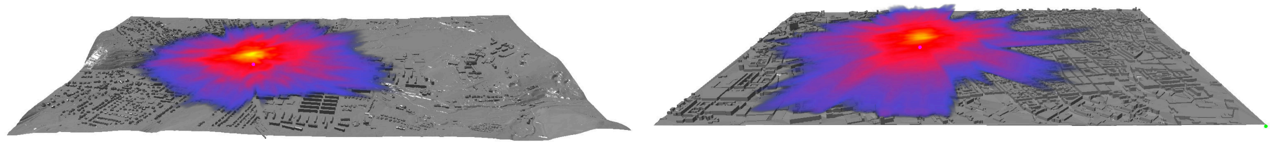

Fig. 1. The two test scenarios as predicted by the Photon Path Map: Ilmenau (left) and Munich (right).

III. BEAM TRACING (2.5D SETTING)

The basic idea of our algorithm is to generate beams that emanate from a radiation source, and split those beams by a rasterization step, recursively creating new secondary beams, leading to a beam tree. Beams are evaluated by a second rasterization step, which produces a 2D field strength map and a delay spread map, which uses 2D position information and an additional dimension to store the impulse response time.

A. Algorithm

The beam splitting is done according to visibility implied by the geometry specified in a building database of the urban scenario. The method is described in more detail in a previous work [16]. The pseudo code for the beam generation is this:

Build scene geometry quadtree
for beam $b \in$ initial beams **do** TRACE(b)
end for
procedure TRACE(b)
    Clip scene against b using quadtree
    Split b according to visible geometry
    for i in split **do**
        Generate reflected, transmitted, diffracted beam b_i
        Update signal time and attenuation for b_i
        TRACE(b_i)
    end for
end procedure

We use a custom rasterization pipeline implemented purely in software on the CUDA platform. We use this custom technology, because the normal OpenGL pipeline does not offer the flexibility we need for the delay spread calculations. The beam evaluation and rasterization step is:

for beam b in beam tree **do**
    Rasterize beam attenuation into 2D array
    Rasterize beam delay into 3D space-time histogram
end for

B. Parameter optimization

We developed a scheme for adapting model parameters from real-world measurements to account for characteristics of different propagation environments and to estimate the influence of unknown components like traffic or vegetation. Our method works well for urban outdoor scenarios, which can be represented well by using a simplified 2.5D model.

We formulate the adaption of model parameters as a constrained least-squares problem in order to minimize the mean squared error between predicted and measured data. The function to be minimized is:

$$f(x_0) = |M \cdot x_0 - s| \tag{1}$$

Where M is a matrix with each row corresponding to one measurement location. Each column is then formed by the travel distance and number of reflections and diffractions of the arriving beams at the respective location. The vector s contains the measured path loss at each measurement location. This allows us to estimate propagation parameters x_0 for each path segment or column in the matrix. They model the reflection coefficients at each intersection point.

IV. PHOTON PATH TRACING (3D SETTING)

The 3D ray tracing method is based on our previous work [7], which we enhanced for better performance and accuracy.

A. Algorithm

The method computes a 3D signal strength map (Figure 1) and an optional delay spread map for arbitrary scene models, both indoor and outdoor. However, here we will focus on outdoor applications. The photon path map algorithm is described for comparison with the beam tracing approach:

for each source s **do**
    for $i = 0$ to n **do**
        TRACE(s, random photon p)
    end for
end for
procedure TRACE(o, p)
    $i \leftarrow$ Compute intersection for $r = o + \lambda\overline{op}$
    Store path segment $P = \overline{oi}$
    if random decision: do not absorb p **then**
        $q \leftarrow$ reflect, transmit or diffract p
        TRACE(i, q)
    end if
end procedure

For a large number n of photons, this gives us a representation of the propagation paths of the radio waves. To get an estimate of the signal strength we then apply the following density estimation algorithm:

procedure DENSITYESTIMATE
    for each stored path segment P **do**
        draw 3D voxelized line for P in image I
    end for
    Apply speherical Gaussian blur on I with radius r
end procedure

The Gaussian blur is needed to get a smooth energy density estimation, and is equivalent to computing the kernel density estimate using a three dimensional Gaussian distribution.

This leads to a very general algorithm, which can be used for indoor as well as outdoor scenes. Scene geometry, transmitter characteristics and material parameters need to be supplied by the user. The result will be a 3D signal strength map for the whole simulation domain. In our previous work, we also showed how to gain impulse response timings from this data.

The photon tracing step and the Gaussian blur are both implemented to run on the GPU. Hence they are massively parallel and very efficient. The 3D rasterization of the photon paths are currently implemented on the CPU, since they involve incoherent, random access of memory, which does not scale well on current GPUs. Instead, we use OpenMP to distribute the workload on all available cores of the CPU.

B. Parameter optimization

In order to generate high accuracy results we implemented a slightly different parameter optimization scheme, compared to the beam tracing algorithm. For the photon path tracing we used the Levenberg-Marquardt algorithm. However, the parameters we optimize for are the material parameters (reflectivity, transparency) of the modeled objects and the antenna gain. This is a rather simple model of the real world conditions and amounts only to a few unknowns, since we assign the same material to most buildings. A separate material is assigned to the ground. The function that is minimized is:

$$f(x_0) = |g(x_0, p) - s(p)| \qquad (2)$$

Where x_0 is the parameter vector, $g(x_0, p)$ are the signal strength values at positions p for the given parameter vector, and $s(p)$ are the actual measured values at positions p.

V. Comparison

Obviously, the 2.5D model of the Beam Tracing approach is a simplified representation of the real world scenario and will not produce optimal results in some situations. But for reasonable urban scenarios our proposed method works well. This holds for the assumption that the ground around the transmitter is locally flat, so that the 2.5D building geometry approximates the scene well.

We evaluated both algorithms using the same scenes, a data set of the city of Ilmenau by Schneider et al. [17] and a data set of the city of Munich [4]. For the Ilmenau set the 3D geometry contains 255.069 triangles. The 2D version for the beam tracing algorithm still contains 127.784 triangles, namely all the buildings of the city. In the Munich data set the 3D scene geometry contains 79.195 triangles.

The beam tracing algorithm takes about 2 seconds compute time for each data set. The time for the Photon Path Map computation is about 16 seconds for each data set. This was measured on a quad-core i7 920 at 2.6 GHz using a GeForce 285 GTX GPU. Thus both algorithms are quite fast, and the beam tracing even allows almost interactive exploration of the radio propagation simulation.

Base Station	RMSE (dB)		Measurements
	Beam	Photon	
BS1	6.9	7.2	842
BS2-1	6.2	5.1	403
BS2-3	4.7	5.2	98
BS3	-	3.4	52

TABLE I
Optimization results, Ilmenau scenario.

Route	RMSE (dB)		Measurements
	Beam	Photon	
0	6.0	8.6	971
1	6.0	8.7	356
2	9.4	7.7	1032

TABLE II
Optimization results, Munich scenario.

A. Parameter optimization

One difference between the two algorithms is that we tried to minimize the error for each reflection step in the beam tracing algorithm, while optimizing the material parameters in the photon path tracing method. The first approach was viable, since the world model in the beam tracing approach was 2D and there was only a small number of beams. For the 3D photon path tracing, this is not efficient anymore, since the matrix M would become much too large, while not being sparse.

Instead we opted to minimize the simulation error by computing material parameters and the antenna gain. For the material models that we use, this gives us around five different parameters per scene. This results in less degrees of freedom than in the beam tracing method, which usually has about 20 parameters, corresponding to 20 reflections. However, the 3D simulation itself is more accurate, so that we end up with comparable results in the end. We furthermore noticed that using more material parameters and probably also a free-space damping parameter could help the photon path tracing even further improve its quality. This will allow the minimization process to model effects that are not explicitly contained in the 3D scene model.

Table II shows that both algorithms perform similarly on the Ilmenau data set. The beam tracing has sometimes an advantage, due to it having more degrees of freedom for the model parameters. The beam tracing algorithm could not be tested on the BS3 data set, since it contains too few measurement points, which are also distributed over too small an area. This was not a concern for the photon path map. Figure 2 shows plots of both algorithms' predictions compared to real measurements.

For the Munich scenario we get similar results. The beam tracing also has an advantage in this case, due to the high number of degrees of freedom. The photon path map shows about 8 dB of RMSE with just three degrees of freedom. It remains to be investigated if more parameters would help to improve the simulation, but the better results in the Ilmenau scenario with five degrees of freedom suggest this. Figure 3 again shows the plots of the performance of both algorithms compared to measurements.

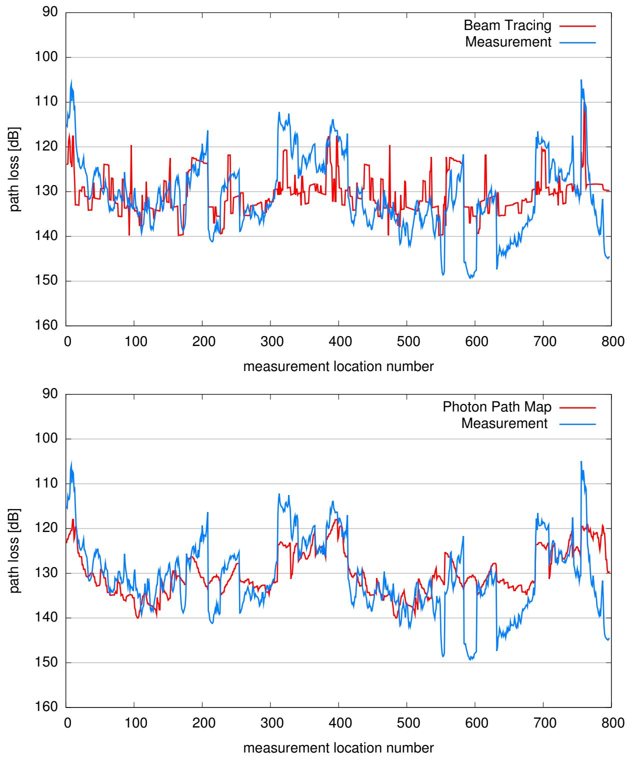

Fig. 2. Results of the prediction for the Ilmenau BS-1 scenario for the Beam Tracing (top) and Photon Path Map (bottom).

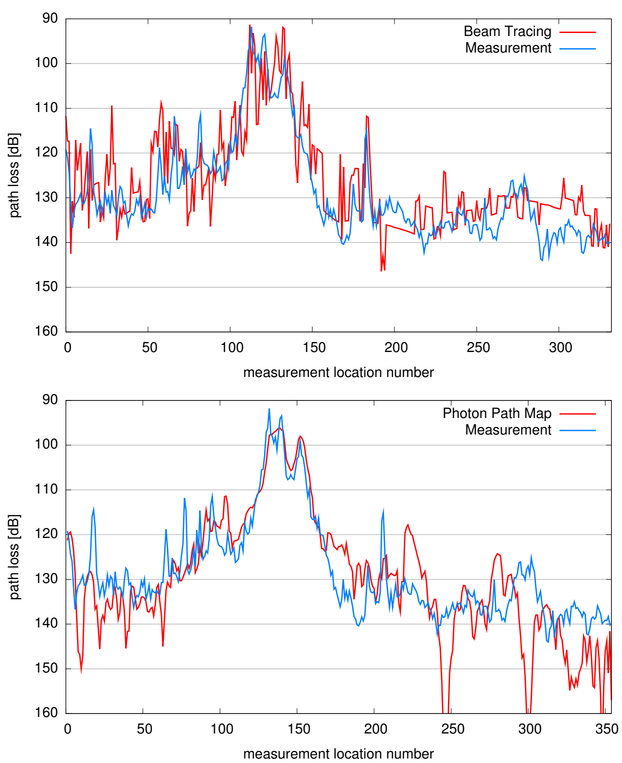

Fig. 3. Results of the prediction for the Munich route-1 scenario for the Beam Tracing (top) and Photon Path Map (bottom).

VI. Conclusion

We presented and compared two different radio wave propagation algorithms for urban outdoor scenarios. Both methods employ a non linear minimization algorithm for parameter optimization. This leads to accurate results. We noticed that a higher degree of freedom for the parameters seems useful, and we will study this in detail in a future work.

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