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A Novel Approach to Mobile Outdoor QoS Map Generation

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***Abstract*—Ray Tracing is an electromagnetic wave propagation modeling approach used for accurate generation of Quality of Service (QoS) maps in mobile networks. Due to its complexity, current implementation of Ray Tracing fails to generate such maps in wide areas. In this paper, we propose an optimization to Ray Tracing able to accurately generate QoS maps in a reasonable time. Using a site-specific ray launching technique and an alternative to the reception test process, we divide by almost 1200 the execution time of Ray Tracing with less than 2% of memory usage as compared to baseline solutions.**

***Index Terms*—Ray Tracing, QoS map, optimization**

I. INTRODUCTION

Ray Tracing (RT) is an electromagnetic wave propagation modeling approach that accurately estimates the signal power received at a given location. RT's accuracy comes from its ability to consider fine-grained information about the environment of interest. Indeed, according to RT, the interaction between waves and buildings is taken into account by different multipath propagation mechanisms [2], [3]. With these mechanisms, the path followed by waves from a transmitter to a receiver is first traced and the corresponding power and bitrate are then computed [6]. Due to the high level of accuracy obtained with RT, it is considered to be an appropriate tool for Quality-of-Service (QoS) maps generation in mobile wireless networks. Examples of QoS maps include the download bitrate and the signal power. Nevertheless, due to hardware limitations, to the big size of the area of interest and to the huge number of antennas and buildings present in the area, it is often impossible to generate those maps using RT. This is mainly due to the discretization process that precedes the map generation. Indeed, during this process, the area is represented as a large set of receiving points, where the bitrate is calculated to produce the map. To obtain a precise map, the distance between those points must be as small as possible. This may lead to thousands and even millions of points generated. The obtained points are considered as receivers and a reception test is performed between them and the rays to determine which rays are being received by the receivers. This process leads to high computational load, high execution time and often memory limit exceeding errors, hence causing the inability to produce the maps. For instance, after 16 hours of execution time on an Intel Core i7 machine with 16GB memory, Matlab's RT implementation crashed due to a memory limit exceeding error and was unable to generate the map in an 1072m x 730m area. This unfortunately makes it impossible for raw RT implementation to generate accurate maps at large scale.

On the other hand, the different RT acceleration techniques such as the space division techniques [5], although very efficient for estimating the signal power of a single receiver, may fail when it comes to generating QoS maps since none of them directly tackles the overhead due to the huge number of receiving points in the area. These techniques mostly care about reducing the complexity related to the ray-object intersection test [5]. Therefore, as the size of the environment and the number of receiving points get bigger, existing techniques become inefficient due to the big matrix operations performed during the reception test process which highly increases the execution time and consumes a lot of memory as in the case of Matlab.

To overcome the inability of the current models and techniques, we introduce in this paper an optimized RT solution able to accurately generate QoS maps in a reasonable time. Where current models as the one of Matlab take 16 hours to execute and often fail due to memory limitations, our solution produces the QoS map within 50 seconds. This is made possible on one hand by the use of a site-specific ray generation technique that we introduced in [1]. This technique helps to launch the optimal number of rays in order to fully cover the area. On the other hand, and instead of discretizing the area, our contribution in this paper is to merely capture the footprint of rays on a given plane rather than performing reception tests on a set of points. By doing so, we remove the discretization and the reception test processes which account for most of the overhead in RT when generating QoS maps.

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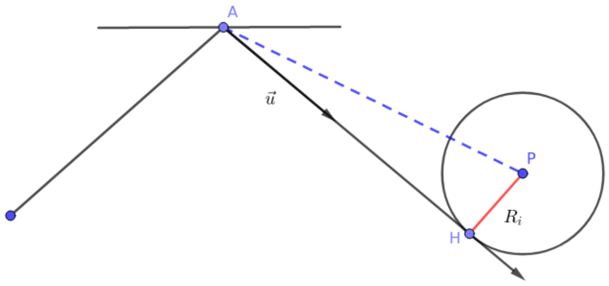

Fig. 1. Reception test process

The main contribution of this paper explained above helps to generate accurate and precise QoS maps at a city or country level in a reasonable time without any memory constraint. Furthermore, by removing the discretization process, our method also removes the need for performing any further interpolation in the discrete case. To the best of our knowledge, this is the fastest tool able to generate QoS maps using RT. As we will see later, we can achieve this goal without compromising the accuracy of the obtained QoS maps.

The rest of the paper is organized as follows. In Section II, some RT fundamentals are explained. The related work is presented in Section III. The system overview is shown in Section IV. We present the validation and the performance evaluation of our solution in Section V. Finally, conclusions and perspectives of our work are discussed in Section VI.

II. RAY TRACING FUNDAMENTALS

Ray Tracing (RT) consists of simulating the different paths followed by rays from a transmitter to a receiver. During this simulation, multiple rays are launched from the transmitter and each of them is tracked by considering propagation mechanisms such as reflection and diffraction. To determine if a ray is received by a receiver, a reception test is performed. Rays are modeled as cones and the reception test consists in checking if the receiver is inside the cones' cross-sections. The radius R_i of a ray cone's cross-section is given by (1) with α_i being the maximum angular separation between adjacent rays and d_i the distance travelled by the i^{th} ray.

$$R_i = \frac{\alpha_i d_i}{\sqrt{3}} \tag{1}$$

The i^{th} ray is received if it passes through the reception sphere of radius R_i centered at the receiver [8]. From Fig. 1, the reception sphere is centered at point P (the receiver). Ray i is received by point P if the distance between P and its orthogonal projection on the ray is less than or equal to the radius of the ray, i.e if $\|\overrightarrow{HP}\| \leq R_i$. Point H, the projection of point P is found using (2):

$$\begin{gathered} AH = \overrightarrow{AP} \cdot \vec{u} \\ H = AH * \vec{u} + A \end{gathered} \tag{2}$$

Now, when it comes to generating QoS maps, the area is discretized into multiple receivers. With M receivers, N rays and K reflections, the matrix calculation in Formula (2) must be conducted $N \times M \times K$ times. For each reflection, the condition $\|\overrightarrow{HP}\| \leq R_i$ has to be checked to identify for each receiver the associated rays that meet the reception test condition. The corresponding received powers are then summed to compute the bitrate for each receiver and to produce the QoS map. The bitrate value is given by the Shannon capacity formula in (3), where B is the channel frequency bandwidth. The signal source (S) is the antenna with the highest signal power whereas other antennas at the same frequency act as sources of interference (I). N denotes the total noise power at the receiver [9].

$$Bitrate = B * log_2(1 + \frac{S}{I+N}) \tag{3}$$

III. RELATED WORK

Different techniques proposed in the literature are used to generate QoS maps. These techniques differ from each other by their level of accuracy and their complexity. The empirical propagation modeling approach for instance, allows QoS maps to be generated after a small execution time using offline calibrated models on real data. These models are fast because they do not consider thorough details about the environment of interest such as buildings and roads. Only with parameters such as the frequency and the distance, these models are able to estimate the received signal power [7]. Although very fast for generating QoS maps, these models suffer from a low accuracy and a weak capacity to account for the details of the propagation environment.

In the same manner, another category of models called the stochastic models is even faster than the empirical ones when generating QoS maps. With stochastic models, the environment is modeled as a set of random variables. A probability density function is used afterwards to estimate the signal power. These models can be very useful for generating QoS maps in wide areas since they do not need a lot of information about the propagation environment for generating the maps. Thus, the maps can be generated with a small execution time [7]. Nevertheless, due to the randomness of this technique and its neglect of environment details, it is the least accurate among all the propagation modeling approaches.

On the other hand, RT can produce accurate QoS maps due to its ability to consider the full 3D map details of the propagation environment. Raw implementation of RT as the one of Matlab allows for example to generate the Signal to Interference plus Noise Ratio (SINR) map of a given area. The SINR can then be used to produce maps of other performance metrics such as the bitrate. Different parameters such as the number of rays to be launched and the resolution (maximum distance between receiving points) are available and can be tuned. For a small area and a large distance between receivers, this model performs well by showing a heat map giving the SINR level of each location in the area of interest [9]. However, when it comes to generating precise maps (small distance between receiving points) in wide areas, the execution time of Matlab's RT becomes very high. Moreover, due to memory limitations, it crashes and gets unable to produce the SINR map. To avoid such issues, Matlab limits for example the coverage area around an antenna to 500 meters. Although this may be helpful in some cases to reduce the complexity of the model, severe accuracy problems occur. Indeed, in real life, some antennas can cover more than 10 kilometers around them and within this radius, hundreds of other antennas may be present. Furthermore, with this setting, potential sources of interference are ignored by Matlab, leading to the generation of QoS maps showing unrealistic results. The larger the number of antennas in the environment of propagation, the higher is the probability of having sources of interference and the worse will be the results from Matlab's RT implementation. This shows the inability of the state-of-the-art raw RT implementation to be used in real life to generate accurate QoS maps at large scale.

To the best of our knowledge, none of the tools in the literature tackles the trade-off between the accuracy and the computational complexity of RT in order to generate accurate QoS maps in a reasonable time. In order to overcome this issue, we introduce in this paper an optimization to RT that allows to accurately generate QoS maps with small execution time. To achieve this trade-off, we simply perform the intersection of ray cones with a fixed horizontal plane Z instead of performing the reception test explained in Section II on different receiving points of the map with different heights. We afterwards use a simple condition to perform the ray-plane intersection test. This helps to drastically reduce the execution time since the need of performing all the matrix operations as in the original RT is removed. Moreover, with our approach, it is no longer necessary to perform the discretization of the map at the reception. Rather, the receivers are considered to be all located on a same fixed horizontal plane. Thus, our method is always precise because all the receiving points in the area of interest are considered. We further improve our approach by coupling it with a site-specific ray generation technique we proposed in an earlier work [1]. With the latter, we are able to launch the minimum number of rays needed to obtain an accurate map. With less rays launched and the reception test process removed, we will demonstrate next how our new method is able to produce accurate maps in a reasonable time.

IV. SYSTEM OVERVIEW

According to standard Ray Tracing, all the rays launched by an antenna need to be tracked and their intersection test with buildings must be performed upon each reflection. Additionally, the reception test between all the rays and all the considered receiving points is performed until the maximum number of reflections is reached. The larger the number of rays and the number of receiving points, the higher will be the execution time of RT, and the better will be the accuracy and the precision of the produced maps.

To reduce the cost in terms of execution time, we solve the complexity related to two main processes of RT. On one hand, instead of launching rays in all possible directions, we use a site-specific ray generation technique. This technique consists of generating the minimum possible number of rays that fully cover the area of interest without any gaps. With this technique, bunch of rays are saved from being wasted, because only potential rays that can reach the receiver are launched.

With RT, the parameter α used in (1) determines the radius of the ray cone. The smaller it is, the more rays are launched and the more accurate the signal power estimate is, but at the cost of higher execution time. Using a larger separation angle α allows a smaller number of rays to be launched, which reduces the computation time needed during the intersection test with buildings and the reception test with receivers. The challenge is to find the larger value of α that does not compromise the accuracy of the maps. This is what we solved in [1], using a site-specific and iterative new ray generation approach. With this approach, we proved that the drop of performance between an angular separation $\alpha = 15°$ and $\alpha = 1°$ is small, i.e., one can reach almost the same level of accuracy with a large value of α than with a small one [1].

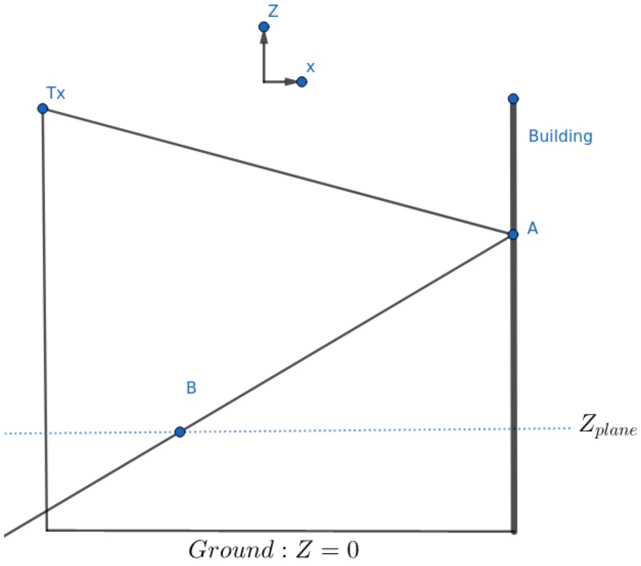

Fig. 2. Ray-plane intersection

The reception test is another cumbersome process to RT as explained in Section II. Indeed, even when smaller number of rays are launched, the large number of receiving points will still lead to an overhead with high memory consumption and complex matrix manipulation. To avoid this, we consider the receivers to be all located on a given horizontal plane Z_{plane}. With this, all the receivers have the coordinates (X_i, Y_i, Z_{plane}). For example, we can consider the receivers to be at the same height Z_{plane} = 1.5 meters. This value typically corresponds to the average height of a person holding a mobile phone.

Fixing the height of the plane has generally little impact as the small variations of the height in the terrain have little effect on the power computed. In future works, we are planning to generalize our method in order to take into account all single terrain variations in the given area. Moreover, fixing

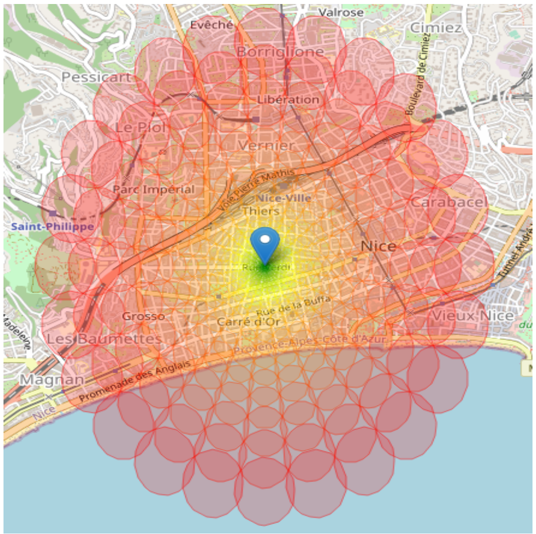

Fig. 3. LOS scenario without any building at $z_{plane} = 1.5$ meters

LOS: RMSE=0.01 Mbps

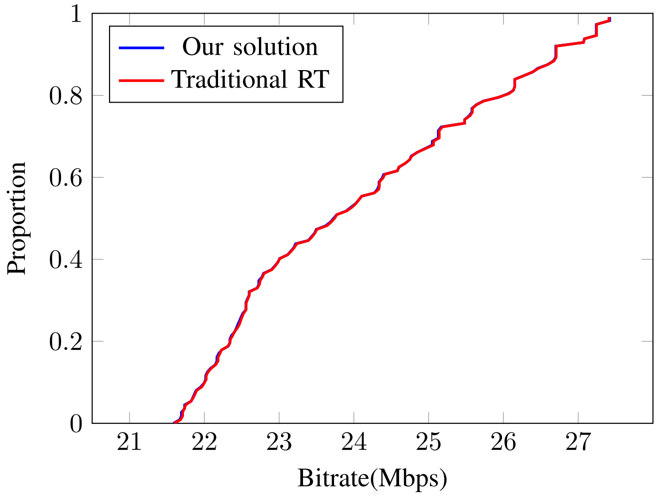

Fig. 4. CDFs of our approach and a traditional RT: LOS

the plane avoids performing the reception test between all the rays and all the receiving points. Rather, an intersection test is performed between ray cones' cross-sections and the horizontal plane of reception to calculate the contribution of the different rays to the QoS map. Since rays are cones, this typically consists in the intersection between a cone and a plane. The plane in the area being horizontal, this intersection is either a circle or an ellipse depending on the incident angle of the ray. For the sake of simplicity, we consider the intersection with the plane to be circles since rays' cross sections are circular themselves with a well-known radius given by (1). The consideration of ellipses would add considerable computation overhead to our approach. However, as we will see in the validation of Section V, the loss in terms of accuracy due to this approximation remains small.

Finally, as shown in Fig. 2, a ray intersects with the plane if condition (4) is met, with $Z_i = Z_A$ being the z-value of the ray previous reflection point A, c_i the z component of the ray's unit direction vector and d_i the distance travelled by the ray between its previous reflection point A and its current endpoint.

$$d_i \geq \frac{Z_{plane} - Z_i}{c_i} \tag{4}$$

Fig. 3 is an example of intersection with an horizontal plane showing the continuous footprints of rays. By removing the discretization, our approach always produces a precise QoS map without the need of having the receiving points to be as close as possible as in the traditional approach. Furthermore, there is no need to interpolate the received signal strength between the receiving points to find the bitrate for unknown points. Indeed, with rays' footprints, every single receiving point in the area is considered during the generation of the QoS map, which leads to a constantly high precision regardless of the targeted resolution.

Note that with our approach, rays may be superposed leading to some areas covered by more than one ray. In those cases, the received power is the sum of the powers of all the rays covering that area, except for double counted rays [8] [4]. In the latter case, the power of the overlapping area corresponds to the power of a single ray. Additionally, we check whether overlapping cones are coming from the same antenna and have the same carrier frequencies in order to consider them or not for the calculation of the interference caused by other antennas. After all these considerations, the bitrate is computed and the QoS map showing the download bitrate as a heat map of the area of interest is generated.

V. PERFORMANCE EVALUATION

When buildings are present in the propagation area, it is not possible for Matlab's RT implementation to have receiving points on the same plane. Indeed, after the discretization process, the heights of the receiving points depend on whether they fall on a building or not. If they fall on a building, their final height is their own height plus the one of the building. Due to receivers having different heights, we could not validate our model using Matlab's RT implementation. To validate our solution, we implemented a raw RT that allows receivers to have the same height regardless of the buildings. However, for the computation load evaluation, the execution time of our solution was compared to the one of Matlab. To do this, we performed different simulations on different terrains with different scenarios. Since our model is free from any discretization unlike the traditional RT, we made possible, for validation purposes, to use our model in such a way it provides the SINR for the individual receivers used in our discrete reference RT implementation.

A. Bitrate validation

In Fig. 4, we see that in the Line-of-Sight (LOS) case, our model has almost the same distribution of the bitrate as our

TABLE I
RMSEs (Mbps) of our model on different terrains

	Line-of-sight	2 reflections	4 reflections
1st Terrain	0.01	2.14	2.69
2nd Terrain 2	0.01	2.55	3.14
3rd Terrain 3	0.01	2.62	3.22

ground truth model with a Root Mean Square Error (RMSE) of 0.01 Mbps. This negligible RMSE means that our model has exactly the same accuracy as the traditional RT in the LOS case. This is because in LOS, the received power is only a function of d^2 [1] (d is the distance of the ray) and since the distances in LOS are typically small, the difference of distances between the traditional RT and our model is small, hence having almost the same received power and consequently the same bitrate. On the other hand, Fig. 5 shows the comparison of the two distributions in case of reflections, with the maximum number of possible reflections sets to 2. We can see that the two models have close distributions with a slight difference in the RMSE. This is because, in Non-LOS, the received power is a function of $\exp(d)$ [1]. Since in NLOS the distances are typically larger, the difference of distances between the traditional RT and our model is not negligible, leading to this slight increase of the RMSE. This difference in the distributions means that upon generating QoS maps for a given terrain, our model makes an average error of about 2 Mbps for 2 reflections. However, we believe this is still an acceptable level of trade-off in terms of time savings as the following subsection will show.

This validation was performed on 3 terrains in the city center of Nice in France. For the sake of our approach generalization, more terrains with different variations in heights will be considered. For now, the simulations performed in Nice were done in LOS, 2 and 4 reflections cases. From Table I, we can see that our model is robust to the change of terrain, since the difference of RMSE in the 3 cases is negligible, i.e., our model keeps almost the same level accuracy regardless of the terrain. Moreover, we also see that our model reaches an acceptable level of accuracy only with 2 reflections.

Next, we show the effect of the angular separation α on the overall accuracy of our model. From Table II, we can see the variation of the RMSE with respect to the angular separation α for 3 different reflections. We can notice from this table that smaller values of α have smaller RMSEs. Nevertheless, the difference of RMSE between the highest value of α and its lowest value is 0.18 Mbps in LOS, 0.67 Mbps with 2 reflections, and 1.62 Mbps in the last case. This means that the drop of performance when going from a small to a large value of α is small. This implies that it is possible to generate a QoS map with the highest value of α and get almost the same level of accuracy as the smallest ones, with the benefit of a lower execution time.

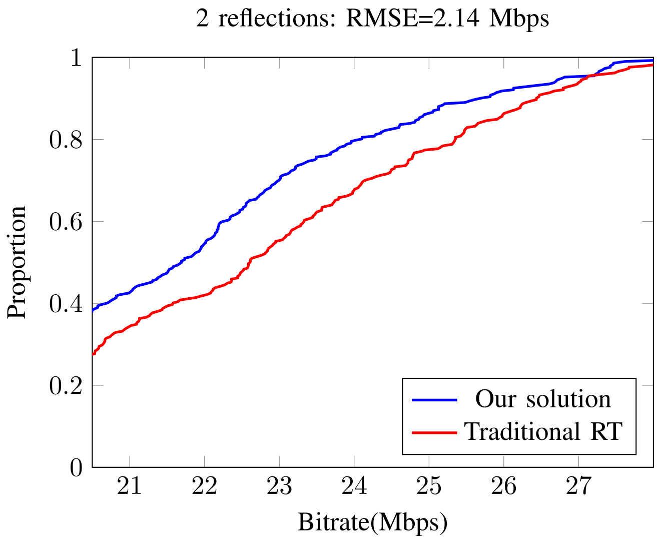

Fig. 5. CDFs of our approach and a traditional RT: 2 reflections

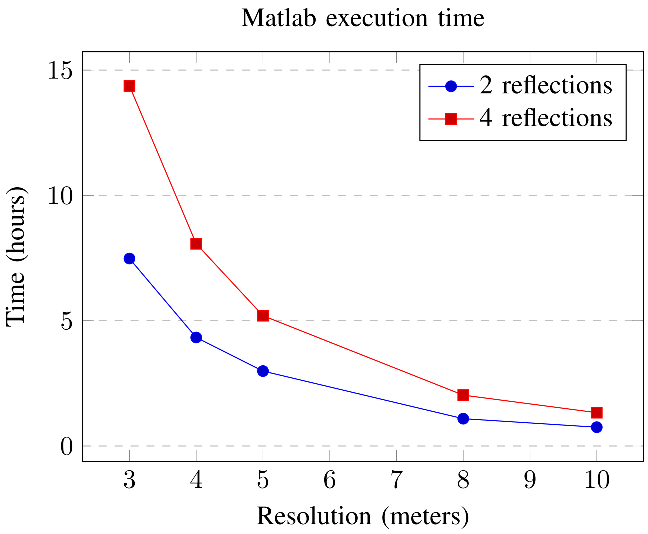

Fig. 6. Matlab execution time

B. Execution time

For the purpose of execution time evaluation, we compared the running time of our model with Matlab's solution, which is a pure RT implementation. Matlab has two fundamental parameters while generating the QoS map: the maximum angular separation (α) and the resolution. The former has to be chosen between *Low, Medium and High*. *Low* is the most accurate angular separation. It launches more rays compared to *High* where less rays are launched but at the expense of a lower accuracy. On the other hand, the resolution is the maximum distance between receiving points. The smaller it is, the higher is the number of receiving points generated and the more precise the QoS map is.

We performed our simulations on an HP ELITEBOOK 850 G7 laptop with 16GB of memory, and a Core i7 CPU @

TABLE II
RMSE (MBPS) SHOWING DROP OF PERFORMANCE AS α INCREASES

α (°)	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
LOS	0.01	0.01	0.02	0.04	0.05	0.05	0.07	0.08	0.09	0.1	0.12	0.13	0.12	0.16	0.18	0.19
2 reflections	2.14	2.09	2.23	2.17	2.66	2.64	2.39	2.68	2.53	2.54	2.95	2.91	2.83	2.9	2.84	2.81
4 reflections	2.69	3.15	3.26	3.21	3.25	3.68	3.63	3.7	3.67	4.04	3.73	3.82	4.36	3.8	3.84	4.31

1.8 GHz. The terrain has a dimension of 1072 meters x 730 meters and is composed of 828 buildings in the city center of Nice in France. Based on this setup, we performed different simulations considering the accuracy and the precision of Matlab's model in LOS and with 2 and 4 reflections. On the other hand, since we proved that increasing the value of α within some range does not alter the model's accuracy, we simulated our model only when $\alpha = 15°$. The latter is the maximum value that α can take due to the small angle approximation made in the site-specific ray generation technique we used [1].

Fig. 6 gives the execution time of Matlab as a function of the resolution in the cases where there are 2 and 4 reflections with *Low* angular separation. In the case of 4 reflections, one must wait almost 1.5 hours to obtain a less precise map and up to 15 hours to obtain a more precise map. In the case of 2 reflections, this value ranges from 45 minutes to 7.5 hours. Given the size of the terrain, this is a very high value. The trend of the graphs shows that this value will increase more and more, that is, the larger the terrain is, the longer the waiting time will be. On the other hand, our approach took **50 seconds** and **2 minutes** respectively for 2 and 4 reflections. This shows the ability of our model to drastically reduce the execution time of RT and to easily scale while producing the map in a reasonable time.

Table III gives a summary of the average execution time of Matlab in seconds as a function of the resolution compared to the time taken by our model. The values for Matlab are the averages over the results obtained for the 3 angular separations allowed in Matlab: *Low, Medium and High*. This table shows that where our model takes 5 seconds in LOS to generate the map, Matlab's model takes on average between 102-709 seconds. On the other hand, our model takes respectively 50 and 125 seconds with 2 and 4 reflections while the time of Matlab is way higher. For larger environments, at country level for instance, Matlab may take days or weeks to produce the QoS map making it not effective for such cases. Moreover, when taking a resolution of 2 meters, Matlab failed at producing the map in the case of reflections. This is due to the large memory consumption generated by RT processes. For example, with 2 reflections and after 16 hours of execution time, Matlab crashed due to this memory issue. This shows that Matlab struggles to generate a precise map for larger environments where the number of receiving points is higher. Whereas our model is not very affected by memory limitations. Hence it can be applied in large scale scenarios with a lower execution time as compared to raw RT implementation as the one of Matlab.

TABLE III
MEAN EXECUTION TIME IN SECONDS OF MATLAB VS OUR SOLUTION

Resolution (meters)	**3**	**4**	**5**	**8**	**10**	**Our model**
LOS	709	422	282	129	102	5
2 reflections	12646	7310	4985	1884	1280	50
4 reflections	23198	13321	8545	3465	2234	125

VI. CONCLUSION

In this paper, we have shown the inability of the current Ray Tracing based models to accurately generate QoS maps in a reasonable time. Indeed, these models fail at generating QoS maps at large scale. With the use of some optimization techniques, we demonstrated that our model could find a good trade-off between computational complexity and accuracy. It is thus able to generate accurate QoS maps within a reasonable time. The consideration of different terrain elevations in our approach will be the topic of a future research work.

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