Propagation Modeling for Accurate Indoor WLAN RSS-based Localization

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***Abstract*—WLAN RSS-based localization has been a hot research topic for the last years. To obtain high accuracy in the noisy wireless channel, WLAN location determination systems usually use a calibration phase, where a radio map, capturing the signal strength signatures at different locations in the area of interest, is built. The radio map construction process takes a lot of time and effort, reducing the value of WLAN localization systems. In this paper, we propose 3D ray tracing as a way for automatically generating a highly accurate radiomap. We compare this method to previously used propagation modeling-based methods like the Wall Attenuation Factor and 2D ray tracing models. We evaluate the performance of each method and its computational cost in a typical residential environment. We also examine the sensitivity of the localization accuracy to inaccurate material parameters. Our results quantify the accuracy-complexity tradeoff of the different proposed techniques with 3D ray tracing giving the best localization accuracy compared to measurements with acceptable computational requirements on a typical PC.**

I. Introduction

Indoor location determination systems have recently attracted a lot of research efforts [1]. WLAN RSS-based localization systems use the Received Signal Strength (RSS) from the available access points (APs) to determine the location of the mobile station [2], [3]. These systems work in two phases, an off-line and an online phase. In the off-line phase, a database (radio map) is built for the RSS from the APs at different locations of the mobile device, a process known as fingerprinting or radio map generation. In the online phase, the received signal at the mobile device is used to estimate the user location from the generated radio map.

The fingerprinting process is a tedious process, requiring lengthy measurements at many locations to build a radio map with the required accuracy. Moreover, these measurements need to be repeated every time a major change in the environment happens. Previous attempts to provide an alternative method for the radiomap generation that avoid manual fingerprinting have suggested the use of propagation models. Propagation models can automatically generate the radiomap, and also account for any changes in the environment. This would significantly reduce the effort and cost for indoor localization systems. The Wall Attenuation Factor (WAF) model was first used in [4], where the radiomap is generated by the free space path-loss model, in addition to attenuation caused by walls. Accuracy of this model was further evaluated in [5]. In [6], an IEEE 802.11 statistical channel model was tested, whereas 2D ray tracing was used in [6] and [7], where the reflections from walls are included in the propagation model.

In this paper, we present a highly accurate method for radiomap generation using 3D ray tracing. This method takes as an input the 3D floor plan of the area of interest, obtained from CAD tools or automatically generated from 2D floor plans, and the location of APs. The 3D ray tracer considers 3D paths between the transmitter and receiver along with their interactions with the materials in the environment. In this model, the attenuation of the rays passing through objects, and the reflected rays from objects, are both angle dependent, as compared to the 2D or WAF models. Therefore, our contributions in this paper are threefold: (1) We propose 3D ray tracing for accurate radio map generation for WLAN location determination systems and describe our 3D ray tracer implementation. (2) We compare the localization accuracy of radiomaps generated using 3D ray tracing to measurements and to the previously used models: 2D ray tracing and the WAF model in a typical residential environment. Our results show that 3D ray tracing provides very high localization accuracy, with a median error of only 3% less than measurements. (3) Finally, we evaluate the sensitivity of the localization accuracy to errors in the model parameters. Our results illustrate the robustness of propagation modeling for radiomap generation to deviations in the used material parameters.

The rest of this paper is organized as follows. In Section II, we describe the different propagation models which will be evaluated. The implementation of the WAF, 2D ray tracing, and 3D ray tracing is described. The localization accuracy of the different propagation models compared to the measured radiomap is evaluated in Section III. Finally, our conclusion and future work are present in Section IV.

II. Propagation Modeling

We will describe below the tested propagation models. A summary of the difference between the used propagation models is given in Table I. In the last subsection, we discuss the parameters for these models.

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TABLE I
SUMMARY OF THE USED PROPAGATION MODELS.

Propagation model	Wall attenuation	Reflections	3D reflection paths	Propagation inside walls	Antenna gain
Wall Attenuation Factor	Included Angle independent	Not included	Not included	Not included	Average gain only
2D ray tracing	Included Angle independent	Included Angle independent	Not included	Not included	Azimuth plane only
3D ray tracing	Included Angle dependant	Included Angle dependant	Included	Included	3D antenna gain

A. *Wall Attenuation Factor model*

The Wall Attenuation Factor model uses the free space path loss model and accounts for the attenuation caused by walls. This model has been used for localization, e.g. in [4], where only the direct path between the transmitter and receiver is considered, and every wall crossed by this path attenuates the passing ray by a constant amount.

B. *2D Ray Tracing*

A more complicated model, 2D ray tracing accounts additionally for reflections from walls and other objects. 2D ray tracing was used for radiomap construction in [6] and [7]. In [7], the electric properties of all walls were treated as being the same, and are estimated from a single measurement point using simulated annealing. In [6], the environment parameters were taken from a database of the floor plan, with different wall types having different transmission and reflection coefficients. We will use the latter approach in our implementation. However, transmission and reflection are angle independent and propagation through the wall structure is not accounted for.

C. *3D Ray Tracing*

3D ray tracing takes into account 3D paths taken by rays and objects with varying heights like windows. We have built a 3D ray tracer for radio map generation, using the method of images [8]. A tree structure holds the images of the transmitter from different reflection surfaces, with the tree size depending on the number of reflections, which is an input parameter. The tree is traversed to form the valid sequences of images. Transmission and reflection from objects are angle dependent, and the propagation losses inside the walls are modeled.

The walls and doors are modeled as homogeneous dielectric slabs. Propagation inside the walls and other objects is given by $E_{out} = E_{in}e^{-j\gamma d}$, where E_{in} and E_{out} are the electric fields at the beginning and end of the path inside the wall, respectively. Here, d is the distance traveled by the ray inside the wall and $\gamma = \alpha + j\beta$ [9]. α and β are functions of the material permittivity ϵ, permeability μ and conductivity σ of the material, and the frequency ω, as given by [9]

$$\alpha = \omega\sqrt{\frac{\mu\epsilon}{2}[\sqrt{1+(\frac{\sigma}{\omega\epsilon})^2}-1]} \tag{1}$$

$$\beta = \omega\sqrt{\frac{\mu\epsilon}{2}[\sqrt{1+(\frac{\sigma}{\omega\epsilon})^2}+1]} \tag{2}$$

Fresnel reflection and transmission coefficients are used, which depend on the incident angle θ_i, material properties, and polarization. For parallel polarization, the reflection co-efficient $\Gamma_\parallel$ and the transmission co-efficient $\tau_\parallel$ are given by

$$\Gamma_\parallel = \frac{\eta_2\cos\theta_t - \eta_1\cos\theta_i}{\eta_2\cos\theta_t - \eta_1\cos\theta_i} \tag{3}$$

$$\tau_\parallel = \frac{2\eta_2\cos\theta_i}{\eta_2\cos\theta_t - \eta_1\cos\theta_i} \tag{4}$$

The transmission angle (θ_t) is related to the input angle (θ_i) by Snell's law

$$\sqrt{\epsilon_2}\sin(\theta_t) = \sqrt{\epsilon_1}\sin(\theta_i) \tag{5}$$

For perpendicular polarization, the reflection co-efficient $\Gamma_\perp$ and the transmission co-efficient $\tau_\perp$ are given by

$$\Gamma_\perp = \frac{\eta_2\cos\theta_i - \eta_1\cos\theta_t}{\eta_2\cos\theta_i - \eta_1\cos\theta_t} \tag{6}$$

$$\tau_\perp = \frac{2\eta_2\cos\theta_i}{\eta_2\cos\theta_i - \eta_1\cos\theta_t} \tag{7}$$

where the impedance η is given by

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}}. \tag{8}$$

D. *Parameters for the Models*

For all site-specific models, a building map is needed. The propagation modeling process is completely automated, as CAD model of the buildings can be imported to the propagation models. Additionally, blueprints of the building can be converted to an electronic building map using image processing [7]. For 3D ray tracing, 3D CAD models can be used. In the absence of such models, a 2D floor plan can be extended to 3D by assuming equal floor height [7].

Electrical parameters for the building material in the test-bed need to be provided for the ray tracer. In [7] and [10], measurements were used to get these parameters. However, since the ultimate goal of using propagation prediction for radiomap generation is to avoid measurements, we will not take this approach. Instead, we will use parameters from the literature directly. Specifically, we use the parameters found in [11], [12] which are listed in Table II. For the 2D ray tracing and WAF models, the transmission and reflection coefficients are constants for each material, given by the last two columns

TABLE II
MATERIAL PROPERTIES USED IN THE PROPAGATION MODELS [11], [12]

Material	ϵ_r	Loss tangent	Transmission coefficient	Reflection coefficient
Brick wall	5.86	0.116	0.6	0.25
Reinforced Concrete	7	0.445	0.5	0.4
Wooden door	2.58	0.2	0.72	0.13
Window	6.38	0.02	0.95	0.276
Wooden floor	2.58	0.2	0.72	0.13
Ceiling	5.86	0.116	0.6	0.25

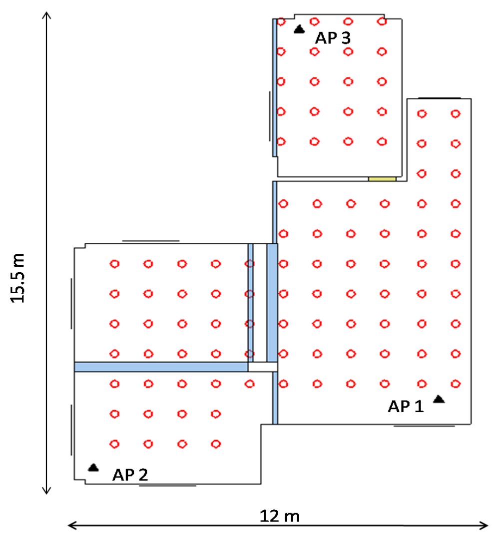

Fig. 1. Top view of the experimental setup. APs shown as triangles, whereas grid points are shown as circles

in Table II. For 3D ray tracing, the material parameters are used. We also investigate the sensitivity of changing the material parameters on the localization accuracy in Section 3.

We have included the antenna pattern for the APs in the ray tracing. The radiation pattern for the used antenna is shown in Fig. 2. For the WAF model, an average antenna pattern of -3dB is used. For 2D ray tracing, we only use the azimuth cut. 3D antenna pattern is needed for the 3D ray tracing. Since a full 3D antenna pattern is not available, we use averaging of the azimuth plane cut $G(\phi)$ and the elevation plane cut $G(\psi)$ to get the 3D pattern $G(\phi, \psi)$ by

$$G(\phi, \psi) = \alpha G(\psi) + (1 - \alpha) G(\phi) \quad (9)$$

where α is a weighting factor that measures how close the ray is to each plane cut, given by

$$\alpha = 1 - \frac{abs(\psi)}{90} \quad (10)$$

III. PERFORMANCE EVALUATION

A. Test-bed

We compare the localization accuracy of 3D ray tracing with measurements and the 2D and WAF models. The experimental

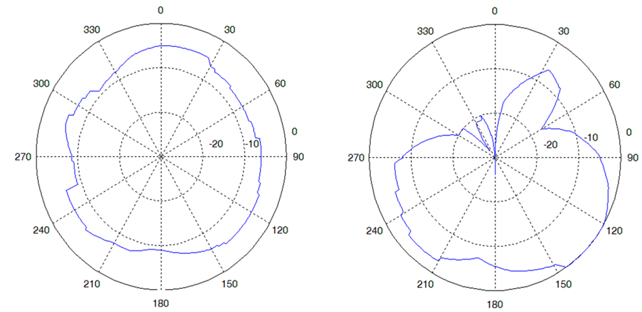

Fig. 2. Antenna pattern for the access points, azimuth (left) and elevation (right) [13].

set-up is shown in Fig. 1. The test-bed is a residential setting with an area of around 130 squared meters. A grid of 101 points is used to generate the radio map, with a spacing of 1m between each point. The radiomap is a table of 101 entries, each entry having 3 average RSS values, one from each AP. Three Cisco Aironet 1130AG access points are used at 2.45 GHz and deployed as shown in Fig. 1. Orinoco Gold PC cards are used with a Dell Latitude D830 laptop, with the laptop held by the user at a height of 1.17m. 100 samples were taken at each point, and the mean of the RSS from each AP is stored in the radiomap. An independent set of 42 points is used to test the accuracy of location determination, with half of the points taken on the same grid as the radio map and the other half in-between the grid points.

B. Location Estimation

Nearest Neighbor in Signal Space (NNSS) method is used for estimating the mobile location from the radio map given the measured RSS [4]. The mobile location is determined by searching the radio map entries. The entry with the smallest Euclidean distance in signal space (composed of RSS from the three APs) is chosen. The random estimator chooses a random point in the grid as the predicted point and acts as a lower bound for localization accuracy.

C. RSS Accuracy

Contour plots of the generated radio-map for AP 1 by the different propagation models are plotted against the measured radiomap in Fig. 3 through Fig. 6. Table III summarizes the results. The figures show that different propagation models follow the general pattern of the measured power. Table III shows that the accuracy of the generated radiomap increases with increasing the complexity of the propagation model: 3D ray tracing has the lowest RMS error compared to measurements, followed by 2D ray tracing and then the WAF model. However, what we are actually interested in is the localization accuracy, discussed in the next subsection.

D. Localization Accuracy

The CDF of the localization error using the different propagation models is shown in Fig. 7. The figure shows that 3D ray tracing has the highest localization accuracy, followed by 2D ray tracing, and then the WAF model. Table IV summarizes

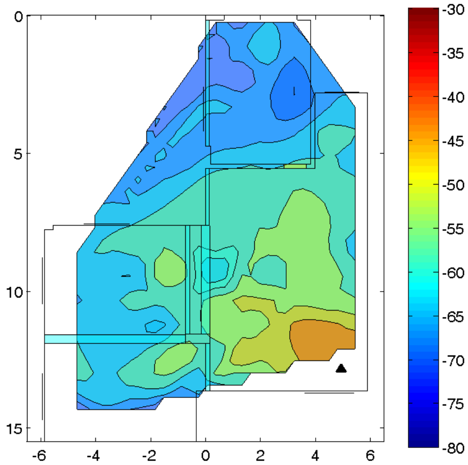

Fig. 3. Contour plot for the received power from AP1 using measurements.

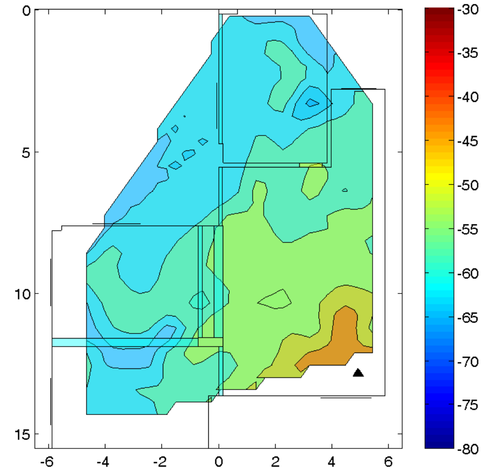

Fig. 5. Contour plot for the received power from AP1 using 2D ray tracing.

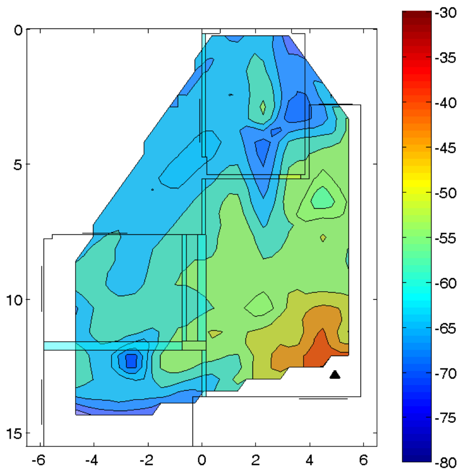

Fig. 4. Contour plot for the received power from AP1 using 3D ray tracing.

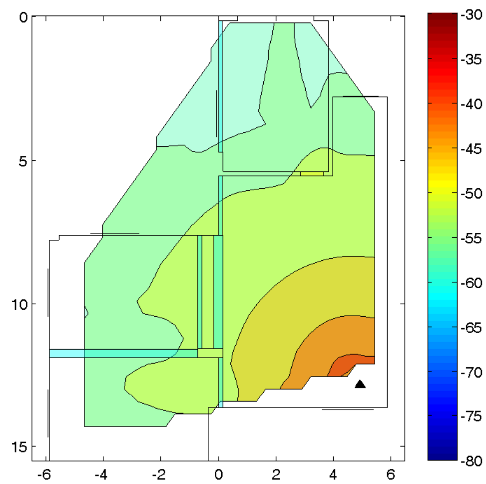

Fig. 6. Contour plot for the received power from AP1 using the WAF model.

the results. The table shows 3D ray tracing is a very accurate method of radiomap generation, with a degradation of only 3% in median error compared to measurements.

E. Running Time

As shown in Fig. 8, the running time for all of the tested propagation models is reasonable. On a typical PC, 3D ray tracing using a single reflection took 17 seconds, 2D ray tracing with also a single reflection took 0.34 seconds, and the WAF model took 0.04 seconds.

F. Sensitivity to Material Parameters

The previous results were based on the material parameters from [11], [12]. In this section, we study the sensitivity of localization accuracy to changes in building materials as reported in the literature [14], [9], [15]. Previous studies, e.g. [16], [17], showed that deviation in ϵ_r ($\pm$ 50%) and σ ($\pm$ 200%) in the used material from the correct value has small effect on the received power prediction in the line of sight case, with a greater effect of σ in the non-line of sight case. However, as indicated, the focus of these studies was received power. Our focus in this paper is on the effect on localization accuracy, specially for the wall material, which we noticed to have the biggest effect on the localization accuracy. In Table V, the median and RMS localization error is shown for different wall parameters found in the literature. The table shows that localization accuracy does not degrade significantly with the change in the wall parameters, which means that we actually do not need to use measurements to obtain the wall parameters.

IV. Conclusion and Future Work

We have explored the radiomap generation for WLAN location determination systems using different propagation models, especially the more accurate 3D ray tracing model, and evaluated the localization accuracy for each model. 3D ray tracing provides the highest accuracy, with only 3% median localization error degradation compared to measurements, followed by

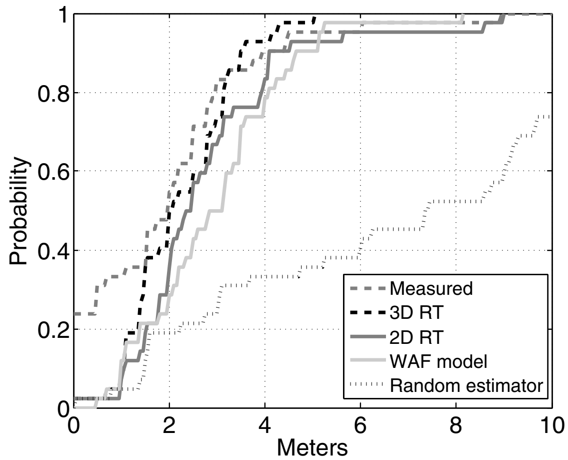

Fig. 7. CDF of the localization error using NNSS estimation.

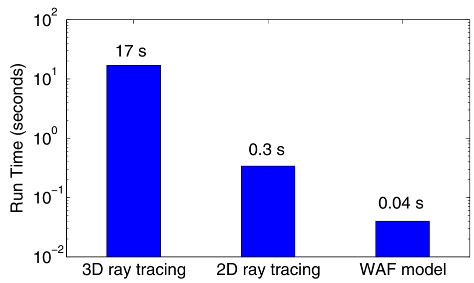

Fig. 8. Simulation time for the different propagation models.

TABLE III
RMS ERROR IN DB FOR THE RADIOMAP GENERATED BY THE DIFFERENT PROPAGATION MODELS COMPARED TO THE MEASURED RADIOMAP.

Radiomap generation method	AP 1	AP 2	AP 3
3D ray tracing	5.58	6.88	8.00
2D ray tracing	5.38	7.39	9.87
Wall Attenuation Factor Model	6.84	8.98	11.53

2D ray tracing, and finally the Wall Attenuation Factor model. 3D ray tracing is relatively more time consuming, though it only takes a few seconds to generate the complete radiomap on a typical PC. We have also shown that deviations in modeling the electrical parameters of the building material has little effect on the localization accuracy. The work shown here is equally applicable to other wireless networks available, like wireless sensor networks. Future work includes investigating the robustness of the different propagation models to changes in the environment. Modeling the effect of people motion and varying densities of human presence in the environment on the localization accuracy is another direction for future work.

V. ACKNOWLEDGEMENTS

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TABLE IV
MEDIAN AND RMS ERROR IN METERS, ALONG WITH DEGRADATION PERCENTAGE WITH RESPECT TO MEASURED RADIOMAP, FOR DIFFERENT RADIO MAP GENERATION METHODS.

Radiomap generation method	Median error	RMS error
Measured	2	1.9917
3D ray tracing	2.07 (3%)	2.28 (14%)
2D ray tracing	2.44 (22%)	2.83 (42%)
Wall Attenuation Factor	3.03 (51%)	2.98 (50%)
Random estimator	7.42 (270%)	6.88 (246%)

TABLE V
MEDIAN AND RMS LOCALIZATION ERROR IN METERS FOR DIFFERENT PARAMETERS FOR THE WALL MATERIAL FOUND IN LITERATURE USING 3D RAY TRACING.

Complex permittivity	Median error	RMS error
3+j0.375 [15]	2.27	2.80
4.44 + j0.02 [9]	2.32	3.09
4.6 + j0.0174 [14]	2.24	2.96
4.6 + j0.0365 [14]	2.16	2.87
5.86 + j0.68 [11]	2.07	2.28

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