MEASUREMENTS AND 3D RAY TRACING PROPAGATION PREDICTIONS OF CHANNEL CHARACTERISTICS IN INDOOR ENVIRONMENTS

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***Abstract*— In this paper path loss, delay and angular spread predictions of a 3D ray tracing propagation tool are compared to spatially resolved wideband radio channel measurements performed in a modern office building. Measurements were carried out in the 5 GHz band by using a wideband radio channel sounder, which gives out complex channel impulse responses. Reference rms delay spread and angular spreads at transmitter and receiver were obtained from SAGE processed super-resolution data, and path losses were available from sounder matched filter outputs after appropriate calibrations. Comparisons between propagation predictions and measurements were made in different indoor scenarios including office, lobby and cafeteria environments. For propagation modelling a full 3D ray optical model was used.**

Index terms: Indoor, radio propagation, channel measurements, delay spread, angular spread, ray tracing

I. INTRODUCTION

The performance of wireless communication systems depends in a fundamental way on the mobile radio channel. Inside buildings the transmission path between transmitter and receiver can vary from simple line-of-sight to one severely obstructed by walls and furniture. As a consequence describing the propagation characteristics between two antennas still belongs to the most important tasks for the design and installation of wireless indoor communication systems. With the upcoming usage of multiple antennas at both ends (MIMO) the radio channel has to be described not only in terms of path loss and delay spread but also with respect to the spatial domain, i.e. including the angles of departure (AoD) and angles of arrival (AoA) for the dominant contributions. Interestingly, direct rms delay spread prediction comparisons are not that frequently seen in published literature, and first angular domain comparisons (to our knowledge) in urban macro-cellular environments have been just recently published [1].

A. Indoor radio channel

The mobile radio channel concerning transmission within buildings is characterized by a multi-path scenario as shown in Figure 1. The signal from the transmitting antenna propagates along different paths to the antenna of the receiver. In many cases there is no direct line-of-sight (LOS) and the only paths connecting transmitter and receiver penetrate either several walls or are reflected, diffracted and scattered at a number of different obstacles. Since the phases of the waves are randomly distributed, the superposition of these contributions causes constructive and destructive interference, which leads to rapidly fluctuating signal levels over very small distances (i.e. small-scale fading). While the small-scale fading is random, the large-scale variations occur due to fundamental changes of the propagation paths (e.g. different obstacles, larger distances). The multi-path propagation leads to a spreading of the transmitted signal in the time and angular domain, which is described by the corresponding parameters, delay spread (DS) and angular spread (AS).

B. Data bases for indoor scenarios

The basis for a ray tracing propagation model is a data base describing the propagation environment. Usually, the buildings have a wide variety of walls and obstacles. According to the magnitude of the penetration loss for electromagnetic waves hard partitions and soft partitions can be distinguished. While hard partitions are formed as bearing parts of the building structure (e.g. walls made out of reinforced concrete or brick, thickness > 10 cm) soft partitions show lower losses (e.g. plasterboard or plywood, thickness < 10 cm). For outdoor modelling, e.g. urban micro- and macrocellular scenarios, transmission through the buildings is not a significant propagation mechanism. In indoor environments, however, transmission through the walls cannot be neglected, since it has a considerable effect in predictions for NLOS areas. Therefore material choices and accuracy of indoor databases may have a significant effect on prediction accuracy.

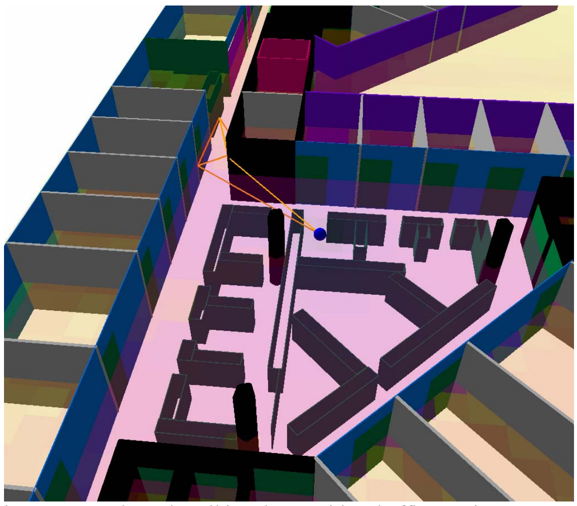

Figure 1: Data base describing the considered office environment and dominant rays for point around corner.

The WinProp radio planning tool [2] stores the building data in a 3D-vector format including all walls, doors, windows (see Figure 1). By the use of such building data bases wireless system designers are able to include accurate representations of building features. In addition to wall,

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ceiling and floor elements the data base can also include furniture, stairs and other relevant objects. Each data base element is described by its coordinates and material properties that have an impact on reflected, diffracted and penetrated rays. For the wave propagation analysis WinProp provides various deterministic and empirical models, among them a sophisticated 3D ray tracing [3][4] which is presented in this paper.

II. Description of the Measurements

A. Measurement set up

Indoor measurements were done at 5.3 GHz carrier frequency and 100 MHz chip rate using a Propsound radio channel sounder of Nokia Research Center, Helsinki [5]. The transmitter and receiver setup used in the measurements corresponds to peer-to-peer communication links, where both the transmitting and receiving devices are about equal height from floor level, and use similar types of antennas. The sounder transmitter and receiver units were installed in trolleys together with TX and RX antenna arrays, the height of which were 1.45 meters above the floor level. The receiver unit was motorized to enable smooth and constant moving speeds. It was moving at speed ~40 cm/s, while the transmitter position was fixed.

As for the antennas, (semi)spherical antenna arrays[1] were used to capture the double-directional channel characteristics. In each array 15 dual-polarized elements around a spherical array were used. With SAGE super-resolution algorithms [6] individual paths could be resolved jointly in delay and angular domain. Table 1 summarizes the indoor peer-to-peer radio channel sounder settings used in the measurements.

Table 1: Channel sounder parameters.

Parameter	Value
Centre frequency	5.3 GHz
Code length	255 chips
Chip rate	100 MHz
Sampling rate	400 MHz
Samples per chip	4
# of RX-channels	30
# of TX-channels	30
Channel sampling rate	10.5 Hz
Array scan time	4.74 ms

B. Environments

Measurements were done in different propagation scenarios in a modern office building. On contrary to older buildings made of brick and concrete, in this building outer walls were mainly made of glass, and inner walls were mostly soft partitions. Measurements were taken in different floors of the building comprising the following cases:

1. Office environment. Transmitter was located in an open plan office area or inside a meeting room. The amount of furniture varies from moderate to dense. Receiver is moving in the same floor inside offices and along corridors both in LOS and NLOS to the transmitter. Maximum TX-RX distance was 25 m, and altogether 130 m of routes were measured for this scenario.
2. Lobby area: Transmitter was located in 2nd or 4th floor corridor (TX heights 4.8 and 11.4 m from the ground level, respectively) behind a glass wall illuminating the open lobby area, which was only slightly furnished. Receiver was moving in the lobby (at ground level). The scenario comprises of altogether 220 m of measured routes, and maximum measured TX-RX distance was 40 m.
3. Cafeteria: Transmitter was located in a canteen or lobby area, and receiver was moving in the same floor in LOS and NLOS to the transmitter. The amount of furniture was little to moderate. Maximum measured TX-RX distance was 40 m, and altogether 230 m of routes were measured.

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III. Description of the Wave propagation Model

A. Deterministic modelling

Deterministic propagation models are generally based on ray optical techniques where different rays emitted by the transmitting antenna are subject to reflection, scattering and diffraction at walls and edges of buildings and similar obstacles. The computations are performed with help of the universal theory of diffraction (UTD) or with empirical diffraction models. The most time-consuming part of a prediction based on ray-optical algorithms is the determination of all the relevant paths from transmitter to receiver. For this purpose either a ray tracing or a ray launching algorithm is used [4]. While empirical models for indoor scenarios assume a dominant propagation along the direct connection line from the transmitter to the receiver, deterministic models consider the physical propagation paths. As a consequence, deterministic models cope with effects such as shadowing behind walls, wave guiding in corridors, offer excellent accuracy and are able to provide additional parameters such as small-scale fading or delay and angular spread.

B. 3D Ray-optical model based on pre-processing

The main disadvantage of the deterministic prediction models is their excessive computation time (in the order of hours). Different authors presented ideas to accelerate the path finding and some of them lead to considerable acceleration factors. However, these approaches consider only the propagation in two dimensions or in two perpendicular planes (horizontal and vertical plane). In contrast to this a rigorous 3D approach is presented in this paper.

For radio network planning a lot of different transmitter locations are evaluated concerning the overall network performance. As the database of the considered building remains the same and only the position of the transmitter changes, the overwhelming part of the different rays remains unchanged. Only the rays between the transmitting antenna and primary obstacles or receiving points in line-of-sight are changing if different transmitter locations are compared.

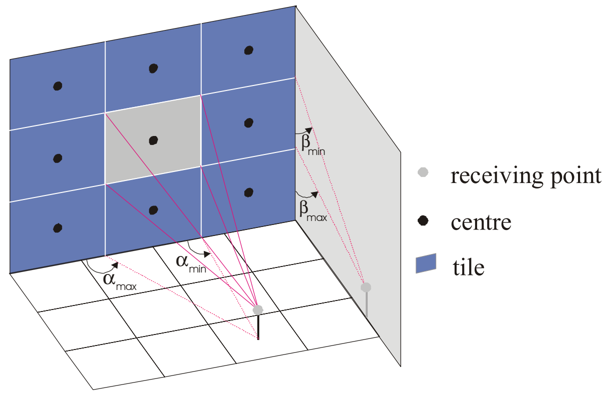

Figure 2: Tiles of a wall and visibility relation.

This is the basis for a "data base pre-processing". In a first step the walls of the building (or other obstacles) are divided into tiles (reflections and penetrations) and the edges (diffractions) into segments. After this, the visibility conditions between these different elements (possible rays) are determined and stored in a file (as indicated in Figure 2). The result of this pre-processing can be represented in the shape of a "visibility tree" (see Figure 3). For a different transmitter location only the uppermost branches in this tree must be computed again, i.e. determining which elements are in line-of-sight to the transmitter. Consequently all other relations have to be computed only once, which can be done prior to optimizing the location of the transmitter. The remaining computation time after the pre-processing is many orders of magnitude lower than that needed for the conventional analysis without pre-processing.

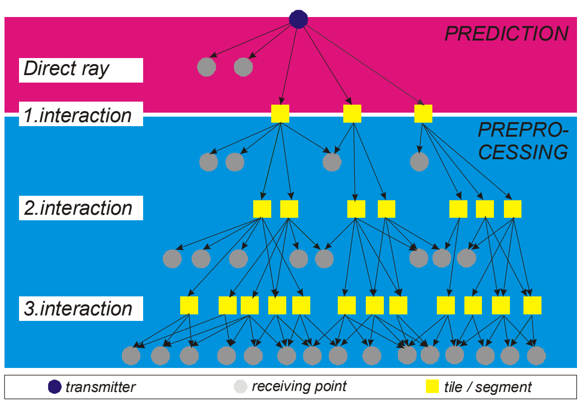

Figure 3: Tree representing the visibility relations.

As a consequence 3D deterministic models with their supreme accuracy can be utilized for all practical applications with computation times in the order of those found with empirical models.

The data bases for this simulation study include walls, ceilings and floors. Additionally the largest pieces of furniture and other obstacles possibly affecting the propagation conditions were considered. Material parameters for concrete, metal, glass, plasterboard and wood were chosen from open literature. For office scenario, tables, shelves and cupboards in the vicinity of transmitter and receiver were modeled (as shown in Figure 1), and for cafeteria scenario tables in the canteen were modelled. Furniture further away inside closed offices was not taken into account, and the lobby area contained no significant pieces of furniture. As for the preprocessing parameters, 2 m was used for both the tile and segment sizes, and for receiver grid 1 m resolution was used.

IV. Results

Reference data from measurements were prepared for comparisons as follows. Rms delay spreads and angular spreads at TX and RX were calculated from data processed with SAGE super-resolution algorithm. SAGE post-processing was done to the measurement data with 20 paths and maximum dynamic range of 25 dB. Estimation of more paths with SAGE would have been desirable for revealing the impulse response shape and different propagation mechanisms, but due to practical limitations of processing time the consideration of more SAGE paths was impossible. Local power delay profiles (PDP) and power angular profiles (PAP) were formed by averaging over ~5λ spatial distance. Thereafter rms delay spread and azimuth angular spreads were calculated from local PDPs and PAPs with 20 dB dynamic threshold from the maximum peak power. Power calibration was made based on measurements taken in LOS conditions in open lobby area by comparing the power of the first arriving peak of the PDP to the free space value at same distance. For path loss calculation received power was then obtained by summing over the delay axis of the calibrated PDPs.

There are different approaches to compare measured and simulated channel characteristics, especially in delay domain. If rms delay spreads are calculated from matched filter outputs, the measurement system bandwidth affects the resulting values. In order to make meaningful comparisons, ray tracing impulse responses should be filtered to match the measurement bandwidth. In our approach we compare directly the super-resolution outputs, which comprise of identified individual propagation paths without system response or antenna characteristics, against ray tracing simulations without filtering. This approach benefits from computational simplicity and equivalent analysis in delay and angular domain. As a drawback, the extracted statistics can be limited due to insufficient number of estimated SAGE paths, or the signal model used in the super-resolution estimation.

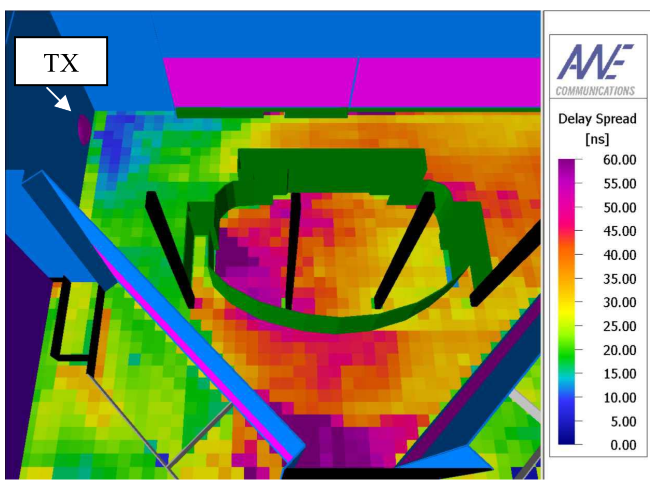

Figure 4: Predicted rms delay spread for lobby scenario with auditorium in the centre (TX is in 2nd floor corridor behind a glass wall, NLOS)

The ray tracing propagation model used in this study is fully three dimensional and computes all rays with four interactions in maximum (up to four transmissions/reflections and double diffractions in arbitrary combinations). Those settings lead to the best relation between computational effort and accuracy. Similar to measurement data analysis, only rays within 20 dB dynamic range were considered for angular and delay spread computations. For the angular spread computations the departing/impinging ray vectors have been added (weighted with their power) in order to avoid the ambiguity with the origin of the coordinate system. An example of predicted rms delay spreads for lobby scenario is shown in Figure 4. Next the measurements and ray tracing predictions are compared in different scenarios: office, lobby, and cafeteria. Figure 5 shows the cumulative distribution functions for measured and predicted rms delay and angular spreads. Corresponding percentiles have been tabulated in Table 2 and Table 3.

Smallest delay spread values were measured in office environment, ~5-25 ns, and the simulated values are well in the same range. In cafeteria and lobby scenarios the measured delay spreads were somewhat greater, ~5-40 ns. The ray tracing prediction could produce similar statistics in cafeteria scenario, but for lobby there is a clear discrepancy between measurements and simulations. Angular spread statistics at TX are fairly well reproduced in simulations for cafeteria and lobby scenarios, but for office case they are clearly underestimated. Measured rms angular spread statistics at RX are fairly similar in all the measured scenarios, typical values being ~25-75 degrees, but simulations show considerably smaller values for all the environments.

Point-to-point comparison results along all the measured routes in different scenarios are summarized in Table 4. An example of comparison of rms delay and angular spreads in cafeteria environment is shown in Figure 6, in which all the measured routes with two different transmitter locations have been combined. For most locations the simulation curves follow the trends and changes seen in measured values, but occasionally great deviations take place. The mean error for rms delay spread prediction is 3 ns, and for rms angular spreads at TX and RX, 4 and 14 degrees, respectively. Path loss mean error in cafeteria environment is 5 dB and standard deviation 6 dB. For comparison, Ref. [7] shows results for rms delay spread at 1 GHz carrier frequency in indoor environment. Also in that case a good correspondence was found, but the used dataset was smaller than in our study, and maximum measured TX-RX distances were shorter, ~15 m.

The discrepancies between measurements and predictions may be due to some relevant scatterers missing from the ray tracing database, or insufficient number of estimated SAGE paths in measurement data. For example, scatterers close to the TX or RX arrays may have a drastic effect on the resulting azimuth angular spreads, whereas change in ray path length is hardly visible in delay domain properties. The second assumption of the number of SAGE paths is more easily verified e.g. by comparing the SAGE power delay profiles filtered to the measurement bandwidth against the power delay profiles obtained from sounder matched filter output. Example of such a comparison is shown in Figure 7. It is clearly seen that the PDP shape is not fully reproduced by 20 SAGE paths, and the resulting delay spread values are therefore very different. In addition, the SAGE signal model does not take into account diffuse scattering, which is expected to affect the shape of the power delay profile. This example also highlights the fact that channel statistics extracted from super-resolution data may sometimes be flawed and an inaccurate reference for benchmarking.

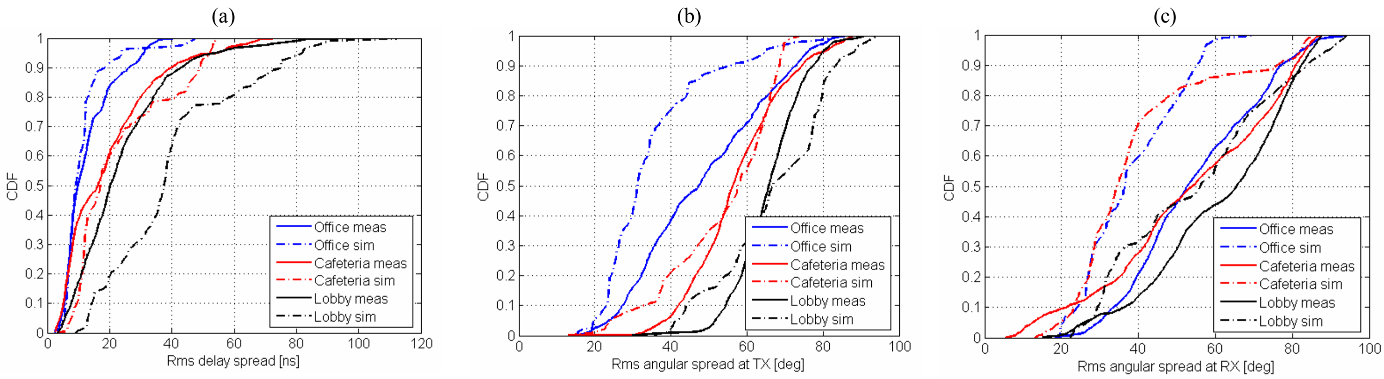

Figure 5: Measured and simulated CDF in different scenarios for (a) rms delay spread, (b) rms angular spread at TX and (c) rms angular spread at RX.

TABLE 2: CDF PERCENTILES FOR RMS DELAY AND ANGULAR SPREAD OBTAINED FROM MEASUREMENTS.

Scenario	Rms delay spread [ns]			Rms angular spread at TX [deg]			Rms angular spread at RX [deg]		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
Office	5.5	9.8	26.1	27.3	47.4	72.8	33.5	52.8	77.2
Cafeteria	5.2	16.2	40.0	42.0	56.2	74.5	21.2	54.0	80.9
Lobby	7.7	20.3	43.0	54.3	65.8	77.5	36.0	65.5	82.4

TABLE 3: CDF PERCENTILES FOR RMS DELAY AND ANGULAR SPREADS OBTAINED FROM RAY TRACING SIMULATIONS.

Scenario	Rms delay spread [ns]			Rms angular spread at TX [deg]			Rms angular spread at RX [deg]		
	10%	50%	90%	10%	50%	90%	10%	50%	90%
Office	6.1	9.2	18.5	23.1	31.2	55.7	24.2	36.6	55.2
Cafeteria	9.5	17.1	49.0	32.7	57.6	68.6	23.3	34.5	76.1
Lobby	14.3	37.5	74.8	44.1	66.7	83.3	29.3	56.0	84.0

TABLE 4: MEAN PREDICTION ERRORS AND STANDARD DEVIATIONS. NUMBERS REFER TO A CASE WHERE RAY TRACING PREDICTIONS HAVE BEEN SUBTRACTED FROM MEASUREMENT RESULTS.

	Rms delay spread		Rms angular spread at TX		Rms angular spread at RX		Path loss	
	Mean	Std	Mean	Std	Mean	Std	Mean	Std
Office	1.4	9.2	13.4	18.0	16.7	19.6	-4.9	5.3
Cafeteria	-3.4	13.2	3.7	15.5	14.0	29.2	4.8	5.7
Lobby	-16.2	20.8	-1.2	17.0	6.6	27.6	-2.1	2.5
All	-7.0	17.4	4.2	17.6	11.9	26.9	-0.1	6.2

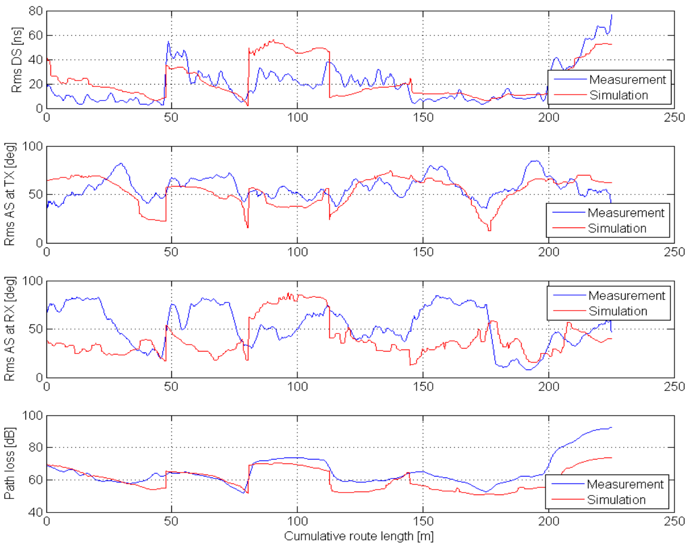

Figure 6: Measured and simulated rms delay and angular spread values in cafeteria environment.

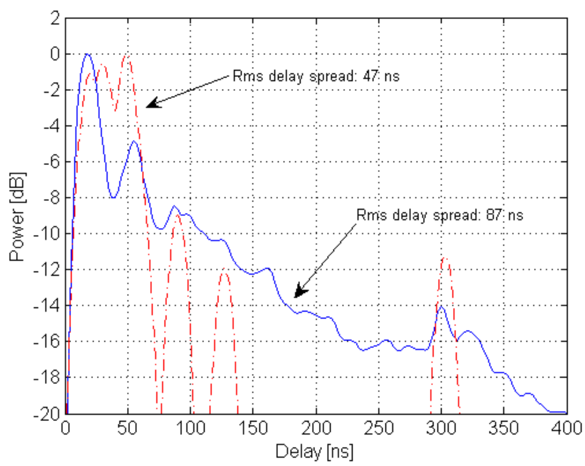

Figure 7: Power delay profiles obtained from measurements. Red dashed line corresponds to 20 SAGE super-resolution paths filtered to the measurement bandwidth, and blue solid line is the PDP from matched filter output.

V. SUMMARY

In this paper path loss, angular spread and delay spread predictions have been compared against data from spatially resolved wideband radio channel measurements. The selected comparison scenarios in this study were challenging in the sense that various environments (office, cafeteria, lobby) require accurate modelling of fully 3D propagation. Especially delay and angular spread comparisons have so far been fairly seldom reported results, although the utilization of also spatial and delay domains of radio channels is of increasing importance. We noticed that the prediction accuracy of the ray tracing tool is greatly affected by the used material parameters and the accuracy of the database. Also processing of the measurements may have impact on comparisons, as was occasionally the case with our results: insufficient number of processed super-resolution paths was identified as one reason behind the discrepancies between measurements and simulated channel characteristics. In addition, the signal model used in the SAGE super-resolution algorithms does not include diffuse scattering, which likely has an effect. With the ray-optical model presented in this paper, the ray tracing predictions in indoor propagation environment gave reasonable accuracy in very short simulation times.

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