Wave Propagation Models for the Planning of Mobile Communication Networks

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Abstract — **The paper gives a survey on a variety of methods for modelling wave propagation in different mobile communication scenarios. The requirements for predicting fieldstrength level and other relevant parameters are discussed for various mobile communication networks including outdoor and indoor scenarios. Apart from well known and widely used propagation models new approaches with minimised computation time are presented.**

I. Introduction

While mobile wireless communication has been a major target of research from the very beginnings of the technical use of radiowaves on, its breakthrough took place not before the availability of solid-state miniaturised transceivers in the 1970s and the development of the cellular concept at about the same time. Since then the exponential growth of mobile communication networks never stopped. As a consequence of the ever growing number of subscribers during the last two decades, the size of cells had to be reduced from radii in the order of tens of kilometres with rural and suburban environments (macrocells) down to few hundreds of metres in urban scenarios (microcells) and even further down to some 10 m with indoor applications (picocells).

With decreasing size of the cells the number of base stations necessary to provide adequate service has to be increased and frequency reuse becomes a must. For an intelligent allocation of base stations and channels planning tools are required that will reliably predict the fieldstrengths generated by the base stations at the receiving end of the downlink (for the uplink generally reciprocity is assumed), as well for the service cell in which the signal must exceed a certain threshold for achieving adequate coverage, as within neighbouring cells using the same frequency for estimating the signal/interference ratio. In certain cases, apart from fieldstrength, other propagation parameters such as delay spread, fast fading, channel impulse response and propagation paths may be required and should be available from the planning tool.

In the following radiowave propagation models are discussed which – on the basis of terrain and urban data bases – allow the computation of the parameters mentioned above. For brevity, main emphasis will be given to the prediction of fieldstrength although reference to the remaining values will occasionally be given.

II. Mobile Radio Channel

The mobile radio channel is characterised by a multipath situation [1]. The signal transmitted by the base station – if only the downlink is considered here – will travel along different paths to the receiving antenna of the mobile station. In many cases there is no direct line of sight and the only signals reaching the receiver have undergone reflections, scattering and diffractions at a number of different obstacles. Consequently the fieldstrength in a radio cell shows small-scale fading and channel transfer-functions of the type given in Fig. 1. While deterministic ray-based propagation models, as described later, are able to compute the small-scale fading, planning tools for the prediction of fieldstrength levels will generally provide only mean or median values as small-scale fading is adequately represented by Rayleigh- or Rice-distributions.

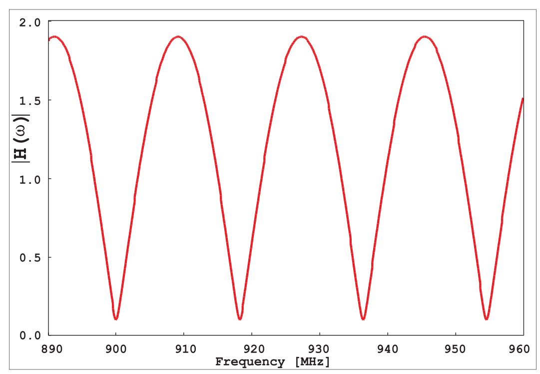

Fig. 1: Magnitude of the transfer function $\underline{H}(w)$ for a two-path scenario with a time difference between the paths $\tau_2 - \tau_1$ = 55 ns and with magnitudes a_1 = 1.0 and a_2 = 0.9

III. Data bases

Data bases used with radio propagation models contain information on the kind of obstacles between the transmitter (base station) and the receiver (mobile station) and are a compulsory requirement for using the more sophisticated prediction tools.

With rural macrocells terrain data bases provide information on the generally irregular terrain beneath and around the propagation path. Most terrain data formats are based on pixels, each representing a rectangular patch of terrain of constant elevation and morphology. In contrast, urban data bases, which contain information on the location of buildings, are generally vector oriented. But pixel data formats, as e.g. obtained by scanning maps, can be converted into vector data [2].

In the vector format, the shape of every building is defined by its corners and its height. All buildings are consequently represented by cylinders with a polygonal plan view (Fig. 2).

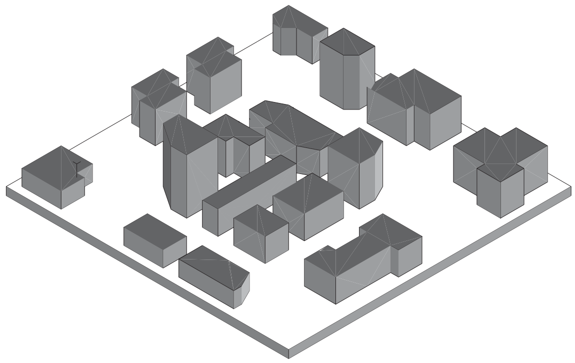

Fig. 2: Example for an urban data base

Indoor data bases are 3D and include all walls, doors, windows and possibly furniture (Fig. 3). All elements inside the building are described in terms of plane elements. Every wall is e.g. represented by a plane and its extent and location is defined by its corners. For each wall individual material properties can be defined [2].

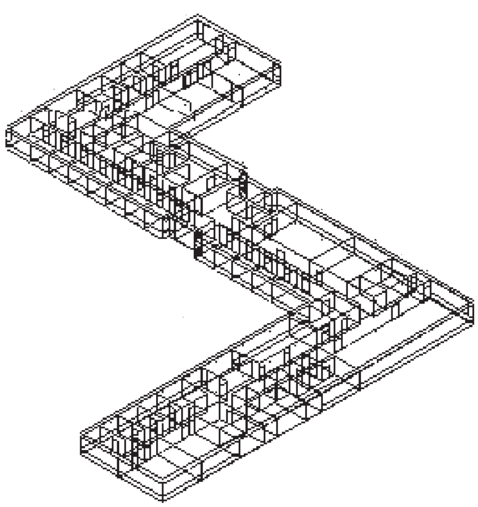

Fig. 3: Example for an indoor data base

IV. Outdoor Prediction Models

While other wireless communication networks, like e.g. directive radio links, operate under line-of-sight (LOS) conditions and can use a simple free space propagation model, mobile communication, as outlined above, is generally non-line-of-sight (NLOS) and requires more sophisticated approaches. In the following some of the most widely employed methods for the prediction of fieldstrength for different scenarios will be discussed and subsequently alternatives, and in particular, more advanced models, which combine accurracy with low computation time, will be presented.

A. Empirical Models

While fieldstrength under free space conditions will – in the farfield – decrease inversely proportional to the distance r from the transmitter, for a scenario including a dielectric groundplane (earth) and assuming reflection with grazing incident angles, it can be shown that in this two-path model fieldstrength now depends on r^{-2}.

A more general approach usually called the *Path Loss Model* assumes r^{-n} with n chosen from experience with wave propagation in different radio environments [3].

Typical values range from $n = 1.4 - 2.5$ for urban environments. The concept can also be applied to indoor propagation with $n = 1.5 - 3.0$. Measurements in typical environments are necessary to find appropriate values of n.

The *Okumara-Hata* propagation model [4] is based on extensive measurement data which have been condensed into an empirical equation. As the range of validity of this equation is restricted in frequency and minimum distance from the transmitter and mainly applies to urban and suburban environment, many improvements have been presented after doing measurements under different conditions and using regression techniques for gaining equations that will take many parameters such as topology and morphology of the terrain along a longitudinal section of the path between transmitter and receiver into account [5].

All empirical models offer short computation time but suffer from limited accurracy.

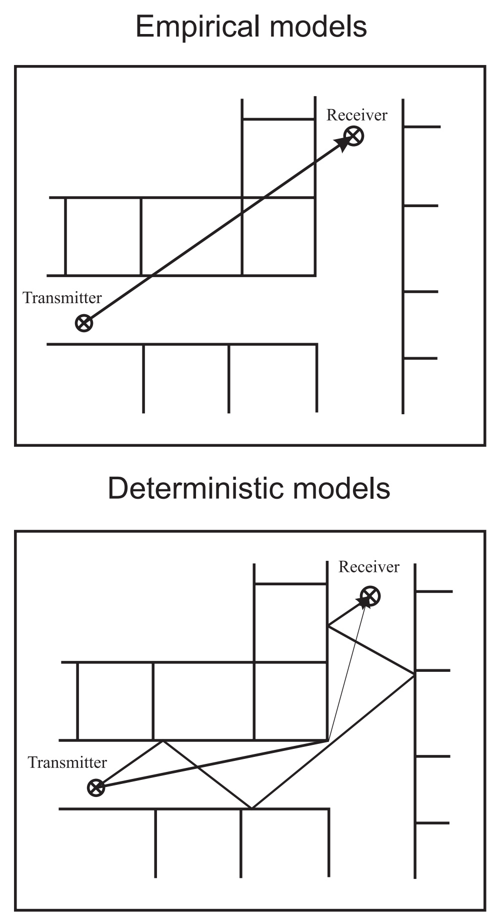

Fig. 4: Prediction models

B. Deterministic and Semi-Deterministic Models

Deterministic propagation models are generally based on ray optical techniques [6], [7], [8], [9] . Their common idea is to describe wave propagation by different rays that travel from the transmitting to the receiving antenna and 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) [10]. The most time-consuming part of a field-prediction based on this method is finding all the relevant paths from transmitter to receiver. For this purpose either the ray tracing [11] or the ray launching [12], [13] algorithm is used (see Fig. 5). Fig. 4 shows the basic difference beween the empirical and the deterministic approach. While the former assumes straight propagation from transmitter to receiver, regardless of any obstacles such as buildings or walls, the latter considers the physical paths along which the transmitted waves propagate. As a consequence, deterministic models cope with effects such as waveguiding in street canyons, offer excellent accurracy and are able to provide additional parameters such as small-scale fading, delay spread etc. Their main disadvantage consists in their sometimes prohibitively large computation time.

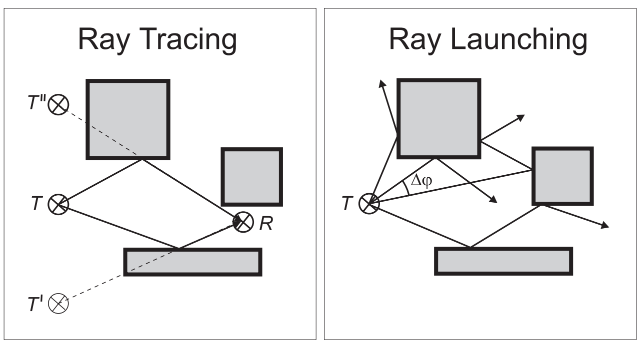

Fig. 5: Algorithms for path finding

Deterministic ray optical wave propagation models can basically be applied to all kinds of mobile communication scenarios from macro- to picocells including indoor propagation [14]. In order to save computation time, instead of a full 3D-approach, in some applications, reflections and diffractions are considered only in the vertical plane or in two principal planes [6], [15], or diffractions are neglected altogether.

A further reduction in computation time is achieved by combining empirical models with deterministic techniques (semi-deterministic models).

An example is the *Walfisch-Ikegami* or *COST-231 model* [3], which is particularly suited for urban radio cells. The basic idea is that in street canyons of densely populated areas the principal wave incidence at the receiving antenna will be due to a diffraction at the roof top of the building next to the receiver in the direction of the transmitter (see Fig. 6). For computation of the diffraction the building is replaced by a semi-plane. Empirical corrections are used e.g. for different heights of the transmitting antenna with relation to the roof tops.

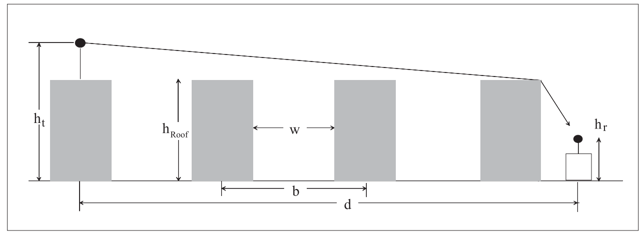

Fig. 6: Basic approach of the Walfisch-Ikegami and COST-231 model

C. Advanced Models

In order to overcome the disadvantages of empirical and deterministic propagation models, viz. limited accurracy or prohibitive computation time, one can either use entirely new models or reduce the computation time of deterministic models by an appropriate preprocessing of the data base.

An example for using an entirely new approach is given in Fig. 7, which shows the result of applying the concept of *Parabolic Equations* to the problem of a wave propagating over hilly terrain [16]. Other examples for this technique will be presented at the conference.

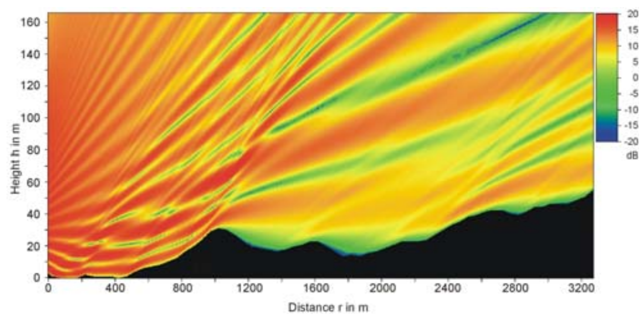

Fig. 7: Computation of the path loss in a vertical plane with the parabolic equation method for DAB broadcasting (frequency 1500 MHz)

One of the major applications of fieldstrength prediction tools is to evaluate the degree of coverage that can be achieved in a radio cell depending on the position of the base station. If the prediction area (the cell) remains the same and only the position of the base station changes, the overwhelming part of the rays remains unchanged, only the rays between transmitting antenna and primary obstacles or receiving points in line of sight change. This is the basis for an *Intelligent Data Base Preprocessing* [17], [18].

In a first step the walls of the buildings (or other obstacles) are divided into tiles (reflections) and the edges (diffractions) into horizontal and vertical segments. After this, the visibility conditions between these different elements (possible rays) are determined and stored in a file. Fig. 8 gives the visibility relations between a central tile and a receiving point. The result of this preprocessing can be represented in the shape of a 'visibility tree' as given in Fig. 9. For a different base station location only the uppermost branches in this tree change. Consequently all branches below the 1st interaction layer have to be computed only once, which can be done prior to optimising the location of the base station. The remaining computation

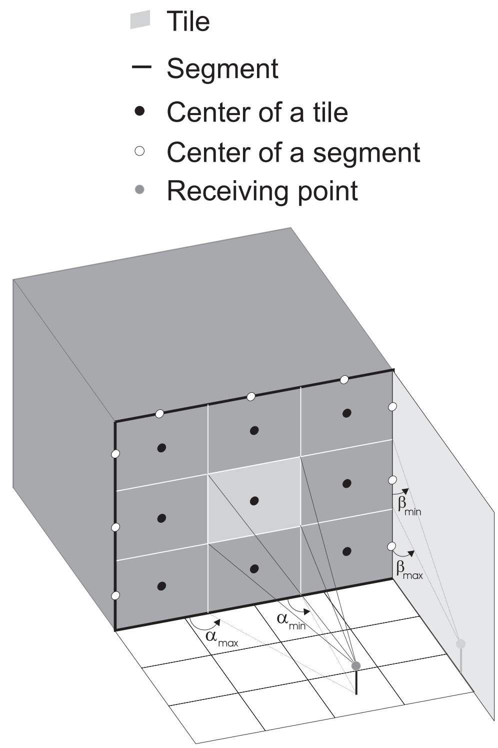

Fig. 8: Tiles and segments of a wall

time after the preprocessing is many orders of magnitude lower than that needed for the conventional analysis without preprocessing. As a consequence 3D deterministic models with their supreme accurracy can be used for all practical applications with computation times in the order of those found with empirical models. Fig. 10 gives an example of a prediction for a Munich scenario using this technique. Table 1 compares the results with measurements and with results of the semi-empirical Walfisch-Ikegami-model.

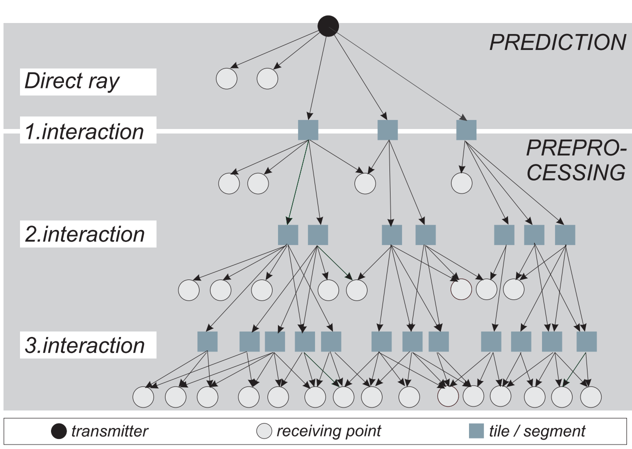

Fig. 9: Tree structure of the visibility relations

Additional methods for accelerating ray optical models are given in [11].

V. Indoor Prediction Models

The path loss propagation model, as outlined above, can also be utilised for indoor scenarios [3]. However, it does not account for the fact that inside buildings, waves can also

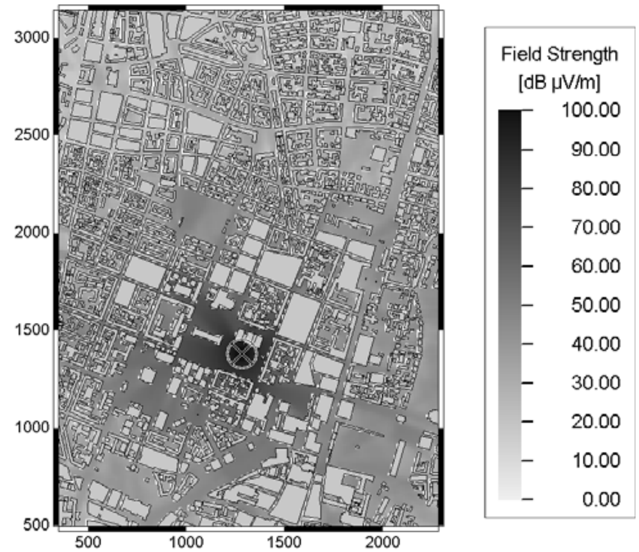

Fig. 10: Prediction for the scenario in Munich with ray tracing

	COST 231		3D Ray Tracing	
	Mean Error	Standard-deviation	Mean Error	Standard-deviation
Route 0	-3.9 dB	7.4 dB	0.5 dB	6.5 dB
Route 1	-4.7 dB	7.7 dB	0.1 dB	4.2 dB
Route 2	-6.9 dB	9.0 dB	-0.6 dB	5.8 dB

Table 1: Accuracy of the predictions for Munich

penetrate walls and that such waves can – under certain conditions – also constitute the main contribution to the total fieldstrength.

This fact is e.g. considered in the *Multi-Wall-Model*, which introduces additional losses for every wall along the direct path between transmitter and receiver [3]. Fig. 11 shows a prediction with the Multi-Wall-Model in an office building.

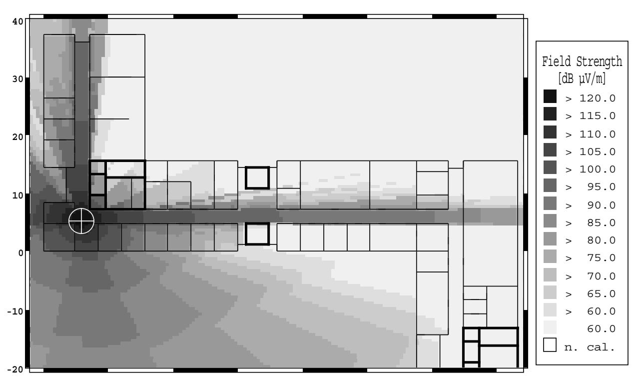

Fig. 11: Prediction with Multi-Wall-Model with $f = 1800$ MHz, $P_S = 10$ mW and isotropical antenna pattern

As waveguiding effects play a dominant part with indoor wave propagation (corridors), most empirical models, as they do not consider this fact, suffer from inadequate accuracy. 3D deterministic propagation models can cope with the situation, but the number of rays that has to be considered is considerably higher than with outdoor scenarios. Although the principle of intelligent preprocessing of the database can also be applied and computation times be drastically reduced, the dependence of the results on the accurracy of the data base is still much more pronounced than with microcell applications [19].

An alternative method, combining the accurracy of deterministic and the small computation time of empirical models, was developed in the shape of the *Dominant Paths* concept [20], [21], [22].

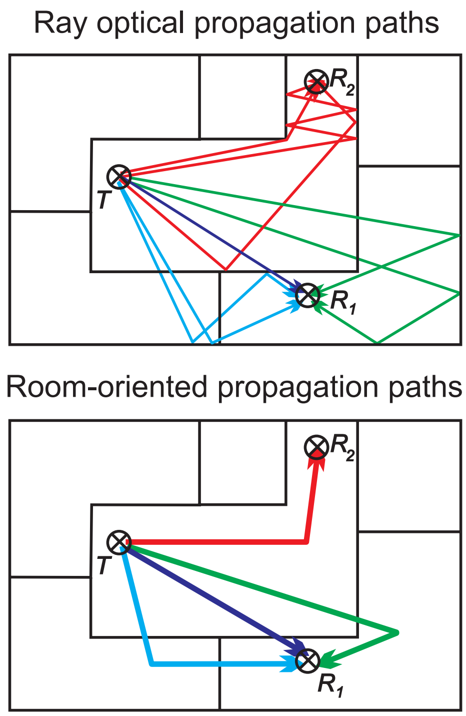

Fig. 12: Dominat paths concept

When drawing rays which contribute to the fieldstrength at the receiving point of a typical indoor situation (Fig. 12 upper half), it is obvious that a number of different rays reach the receiver after passing the same sequence of rooms and penetrating the same walls. In the new concept these rays are summarised into one dominant path, characterising the propagation of a bundle of waves. There is generally more than one dominant path between transmitter and receiver, as shown in Fig. 12 bottom. The dominant paths can be deduced using simple algorithms which consider the arrangement of the rooms within the building relative to the transmitter and the receiver. Only dominant paths which – according to a rough empirical estimate – show the lowest attenuation, are used for the fieldstrength prediction (in many cases the number of paths to be considered does not exceed one or two).

The fieldstrength prediction uses the output of an artificial neural network (perceptron) whose input parameters characterise among other things the waveguiding, attenuating and shielding effects of the rooms and walls through which the dominant paths pass. The neural network is trained from measurements and can thus be adapted to different scenarios such as office buildings, exhibition halls etc.

		Scen. 1	Scen. 2	Scen. 3
Multi Wall	Mean err.	12.4 dB	5.1 dB	16.3 dB
	Std.-dev.	16.8 dB	11.5 dB	20.5 dB
Dom. Path	Mean err.	0.6 dB	1.2 dB	2.5 dB
	Std.-dev.	4.6 dB	3.7 dB	3.8 dB
Ray Trace	Mean err.	0.1 dB	-2.4 dB	2.0 dB
	Std.-dev.	6.5 dB	7.3 dB	11.9 dB
Reference		[22]	[21]	[20]

Table 2: Mean error and standard-deviation for different test scenarios in the new office building in Stuttgart

Table 2 compares typical results obtained with the new method with those achieved from the empirical multi-wall-model and a 3D deterministic ray tracing technique for three different scenarios. Not only offers the new dominant path concept accurracies in the order of the deterministic model but its computation time is also similar to that of the empirical one. In addition the dominant path approach is – in contrast to ray optical techniques – robust against inaccuracies of the data base [20], [21]. Fig. 13 shows an prediction with dominant paths for a transmitter location identical to that of Fig. 11.

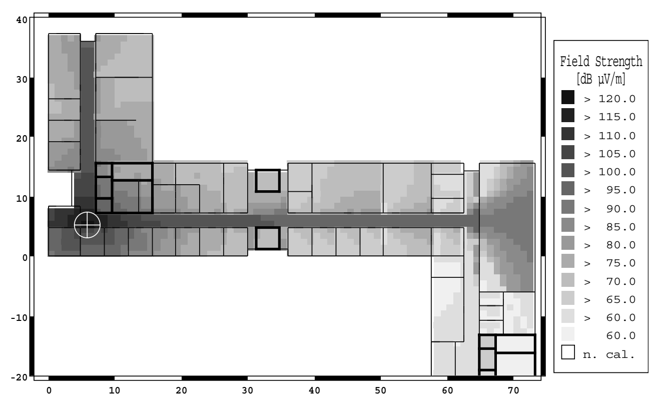

Fig. 13: Prediction with dominant paths with $f = 1800$ MHz, $P_S = 10$ mW and isotropical antenna pattern

VI. Conclusions

A variety of propagation models, which can be used for fieldstrength prediction methods in connection with the planning of mobile cellular radio networks, has been presented for indoor and outdoor scenarios. It has been shown that with new concepts the advantages of deterministic and empirical wave propagation models can be combined without adopting their drawbacks.

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