A Hybrid Ray-Tracing/Vector Parabolic Equation Method for Propagation Modeling in Train Communication Channels

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Abstract—In recent years, various techniques have been applied to modeling radio-wave propagation in railway networks, each one presenting its own advantages and limitations. This paper presents a hybrid channel modeling technique, which combines two of these methods, the ray-tracing (RT) and vector parabolic equation (VPE) methods, to enable the modeling of realistic railway scenarios including stations and long guideways within a unified simulation framework. The general-purpose RT method is applied to analyze propagation in complex areas, whereas the VPE method is reserved for long and uniform tunnel as well as open-air sections. By using the advantages of VPE to compensate for the limitations of RT and vice versa, this hybrid model ensures improved accuracy and computational savings. Numerical results are validated with experimental measurements in various railway scenarios, including an actual deployment site of communication-based train control (CBTC) systems.

Index Terms—Electromagnetic propagation, hybrid channel modeling, parabolic wave equation, ray-tracing (RT).

I. INTRODUCTION

THE DEVELOPMENT of modern communication-based train control (CBTC) systems has led to an increased interest in the study of radio-wave propagation characteristics in railway environments. A prerequisite for the deployment of access points for such systems is the existence of a suitable propagation model, which provides accurate path-loss predictions of corresponding wireless channels. While a propagation model can be obtained using measurements, the development of theoretical models is highly valuable. Such models can significantly reduce the time and effort involved in collecting measurement data, considering that current rail transportation networks extend over tens to hundreds of kilometers.

Several theoretical models, namely waveguide theory, full wave (FDTD or FEM), vector parabolic equation (VPE), and ray-tracing (RT), have been previously adopted to model radio-wave propagation in analogous scenarios [1]–[5]. All these approaches have not only distinct advantages but also significant limitations in terms of accuracy and efficiency. On the analytical side, waveguide theory models have been widely employed [6], [7] for fast, physically insightful yet approximate analysis of propagation along uniform tunnel geometries. However, as practical tunnel, cross-sectional geometries differ from those of standard waveguides (perfectly rectangular or circular), the accuracy of this approach is compromised. A more versatile yet computationally intensive alternative is offered by full-wave methods. However, to model electrically large railway environments, full-wave models are computationally intensive and are not practical even on a super-computing platform [8]. Comparatively, RT and VPE methods have found a prolific area of application in railway propagation studies, striking a better balance between accuracy and efficiency [9]–[11].

RT methods enable propagation modeling in very complicated scenarios such as railway stations, and they can provide reasonably accurate prediction of signal fading characteristics [12]. However, these methods typically have an exponential computational complexity for certain practical problems [13], [14]. Generally, in a scenario with $N$ surfaces and a reflection level of $k$, where the reflection level is defined as the maximum number of reflections per path allowed in the model, the total number of nodes needed to be calculated is $1 + \frac{N(N-1)^{k-1}}{N-2}$ [12]. Despite techniques being developed in recent years to relieve this computational burden [15], [16], the computational cost issues still remain, especially at large distances of separation between the transmitter and receiver, where a larger number of reflected rays are required for convergence. Hence, the application of RT is limited in many critical cases.

VPE methods [17], on the other hand, are far more computationally efficient for long guiding structures such as tunnels and offer prediction with higher accuracy, even if the receiver is far away from the transmitter. Since VPE is derived from the full-wave Helmholtz equation, the effects of reflection, diffraction, and radiation, can be fully taken into account. More recently, improved VPE methods have been introduced to enable propagation modeling in curved tunnels with various cross-sectional geometries [14], [18], [19]. However, VPE methods cannot model high-order modes and corresponding rapid fluctuations accurately [10], and thus, they are limited to paraxial wave
propagation predictions. Moreover, practical antenna patterns cannot be readily incorporated as the initial conditions for VPE.

Therefore, in this paper, a general-purpose RT package [20], [21] is combined with VPE [14]. RT has been previously used to generate initial conditions for VPE [4]. However, it is the first time that a full hybrid RT method is formulated, applied, and evaluated as a unified means of modeling propagation along subway stations, tunnels, and open-air guideways. In this paper, this hybrid model is applied to heterogeneous railway networks (including stations, open and closed guideway sections) within a unified simulation framework. Validation is provided by comparisons with measured data in realistic railway scenarios.

The outline of this paper is as follows. First, in Section II, the proposed hybrid propagation model is introduced. Concrete guidelines for choosing the position of the connecting interface between the two solvers are also provided. Section III presents validation results for the proposed method, based on the widely studied Massif Central tunnel, for which measured data are also available. Sections IV and V present comparisons of our technique to data from measurement campaigns that were performed in a subway tunnel and an open-air environment, respectively. The latter results show the usefulness of this hybrid approach for open-air guideway sections. Finally, the contributions of this work are summarized in Section VI.

II. NOVEL HYBRID PROPAGATION MODEL

A. Implementation

The principle of the proposed hybrid model is to strategically subdivide a propagation channel geometry into two main subdomains—one containing complex geometrical features simulated using RT and the other consisting primarily of long, uniform tunnel sections evaluated using VPE. Therefore, the primary step is to subdivide the simulation scenario into an RT subdomain and a VPE subdomain. At the interface of the two subdomains, a Huygens’ interface is defined to couple the fields generated from one solver to the other. For example, consider the case of a subway system. RT can be applied to the area in and around a station, whereas VPE can be very efficient with long tunnel sections.

The image theory-based ray tracer presented in [21] and [22] is employed to simulate the RT domain and compute the electric fields at grid points specified on the interface which provide the initial conditions needed for the VPE method [23], [24]. The VPE solver is then used to compute the fields throughout the VPE subdomain. For example, as illustrated in Fig. 1, RT is applied to model wave propagation in the first section and is used to generate fields on the connecting interface of the two subdomains. These fields on the interface are then adopted as the initial source plane for the VPE solver. The interface is placed at a position where paraxially propagating fields, satisfying the fundamental assumptions of the VPE method, dominate the total field. Hence, diffracted components are not included in the RT model as our primary purpose is to calculate the path loss at long distances along the tunnel.

Fig. 1. Hybrid model diagram, where the simulation scenario is divided into two subdomains and the dots on the interface represent the discrete-space fields computed from the RT method.

The number of discrete grid points on the interface is chosen by considering the discretization error of the VPE solver. Generally, a mesh cell size of \(0.3 \lambda\) is used to guarantee a phase error smaller than \(0.1^{\circ}\) per cell [25]. For cases where line-of-sight field components dominate, a much larger cell size could be chosen. For example, a mesh cell size of \(0.8 \lambda\) is used for the open-air environment presented in Section V. In [25], the accuracy of VPE methods as a function of mesh cell size is discussed in detail. Moreover, it should be guaranteed that, on the interface plane, the fields generated by RT have converged. This is achieved by ensuring that an appropriate number of reflections is allowed in the RT simulation.

B. Location of the Interface

Since VPE methods are not suitable for modeling complex areas such as railway stations, the interface is generally placed within a uniform section. The function of this interface is basically to transfer fields from the RT subdomain to the VPE subdomain, or vice versa. The main discussion of this section will focus on how to select the interface location in the first case.

To determine where to place the interface for the first case, both the accuracy and the efficiency of the hybrid model need to be taken into account. On one hand, the paraxial assumption of VPE methods [17] should be satisfied at the interface to guarantee the accuracy of the hybrid model. On the other hand, in order to relieve the computational burden of RT and improve the overall efficiency, the interface will be placed as soon as this assumption is met.

One intuitive, yet brute force, approach to determine the interface location is by monitoring the convergence of the path loss calculated via the hybrid method, as the interface is placed at various positions. Then, the position of the interface can be fixed once convergence is achieved.

Alternatively, a more quantitative approach for placing the interface is analyzing how well the assumption for VPE is met directly. On the interface, the electric field at each point can be expressed as

\[
\vec{E} = \sum_{i=1}^{P} \vec{E}_i
\]
where $i = 1, 2, \ldots, P$ represent the individual rays reaching this point and $\mathbf{E}_i$ is the field component contributed by the $i$th ray path. Moreover, these rays will reach this point at various incidence angles. For the standard parabolic equation method [17], [25] that we used in our solver, the second-order derivative with respect to the direction of propagation can be reduced into a first-order derivative, by making the following assumption:

$$\left| \frac{\partial^2 u}{\partial z^2} \right| \ll k_0 \left| \frac{\partial u}{\partial z} \right|$$

where $u$ is the plane wave solution [17]; $k_0$ is the free-space wave number; and $z$ is the propagation direction. One direct perspective to understand this assumption is that the wave propagation is paraxial, which means that the wave travels within a small azimuth angle to the propagation axis. As discussed in [25] and [26], for the standard PE formulation that we adopted in this paper, this assumption corresponds to angles of propagation up to about 15 degrees with respect to the $z$-axis.

Therefore, all the rays reaching the interface at a certain distance are sorted by their incidence angle. They are divided into $0^\circ$–$15^\circ$ and $15^\circ$–$90^\circ$ angle groups, as illustrated in Fig. 2. The corresponding power density for each ray path is

$$S_i = \frac{|\mathbf{E}_i|^2}{2\eta}.$$  \hspace{1cm} (3)

Assuming that there are a total number of $N$ ray paths reaching the interface, and $m$ of them have an incidence angle within $15^\circ$; then, the total power densities due to rays within, respectively, $0^\circ$–$15^\circ$ and $15^\circ$–$90^\circ$ groups ($S_{0^\circ-15^\circ}$ and $S_{15^\circ-90^\circ}$), are calculated as

$$S_{0^\circ-15^\circ} = S_1 + S_2 + S_3 + \cdots + S_m \hspace{1cm} (4a)$$

$$S_{15^\circ-90^\circ} = S_{m+1} + S_{m+2} + S_{m+3} + \cdots + S_N \hspace{1cm} (4b)$$

The power density weight $w$ for the first $0^\circ$–$15^\circ$ angle group is obtained via the following expression:

$$w = \frac{S_{0^\circ-15^\circ}}{S_{0^\circ-15^\circ} + S_{15^\circ-90^\circ}} = \frac{S_{0^\circ-15^\circ}}{S_{total}}. \hspace{1cm} (5)$$

The trend of the power density weight $w$, which is a function of distance, is analyzed. The interface is placed at a plane where the relative contribution of the rays outside $15^\circ$ is insignificant, i.e., the power density weight $w$ exceeds a certain certain threshold. This threshold is chosen according to the desired accuracy and computational efficiency of the hybrid model. A threshold equal to 0.95 is used throughout this paper.

III. VALIDATION: MASSIF CENTRAL TUNNEL

In this section, for the purpose of validation, the hybrid method is applied to modeling wave propagation in a tunnel geometry that has been widely studied in the literature, the Massif Central tunnel in south-central France [27]. It is a straight 3.5-km-long tunnel consisting of large blocks of smooth stones or concrete. The simulated distance is 2.5 km, and the simulated received power at 900 MHz is compared to the measured data, presented in [27]. The transmitter and receiver points are both defined at height $y = 2$ m and at one quarter of the width of the tunnel horizontally. Vertically polarized wideband horn antennas with a gain of 7 dBi are employed. Following [27], we model this tunnel as a rectangular tunnel of cross-sectional dimensions of 7.8 m $\times$ 5.3 m. The electrical parameters of the surrounding walls are set to $\varepsilon_r = 5$ and $\sigma_0 = 0.01$ S/m.

RT is applied to generate the fields of the antenna and inject them into the VPE solver. The spatial discretizations for the VPE subdomain are chosen as $\Delta x = \Delta y = 0.1$ m and $\Delta z = 2$ m. To determine the location of the connecting interface, the total power density of all the ray fields within the $0^\circ$–$15^\circ$ and $15^\circ$–$90^\circ$ groups are calculated. The trends of the power density weight of the two angle groups are illustrated in Fig. 3. The trend is consistent with the analysis in [27] that the near zone of the tunnel is characterized by rapid fluctuations caused by the interaction of multiple modes, and since higher order modes attenuate more severely, the fields in the far zone consist primarily of the first few lower order modes. As can be seen from Fig. 3, after about 400 m, the power density weight of ray fields within $15^\circ$ is above 95%, indicating that the fundamental assumption for VPE is satisfied.
Therefore, the interface could be placed at about 400 m inside the tunnel. To validate this choice, the received power profiles generated by placing the interface at various locations, respectively, at 50, 200, 400, and 500 m, are compared. The comparison is depicted in Fig. 4, where it can be observed that the profiles of the received power remain almost the same after the interface is placed at 400 m, which is in agreement with the analysis of the power density weight and further confirms that the interface could be placed around this distance.

The relation between the execution time and the attenuation slope as a function of the interface location is presented in Table I, where the attenuation slope of the simulated results is obtained by applying a least-squares fitting to the data in the 0.5–2.5-km region. The execution time is counted when the fields generated by RT have converged on the interface. Convergence is achieved when the error norm

\[ E_{\text{rms}} = \sqrt{\frac{1}{M} \sum_{i} \sum_{j} \left| \vec{E}_{i,j}^{k+1} - \vec{E}_{i,j}^{k} \right|^2} \]  

is smaller than 0.05. In (6), \( \vec{E}_{i,j}^{k+1} \) and \( \vec{E}_{i,j}^{k} \) denote the discrete-space electric field on the interface generated, respectively, with a reflection level of \( k+1 \) and \( k \); \( i \) and \( j \) are the discrete-space indices; and \( M \) is the number of the discretization points on the interface.

At larger distances, a higher level of reflections is needed to achieve convergence of RT. It can be seen from Table I that the execution time increases exponentially with the length of the RT region. When the interface is placed at 50 m, just a reflection level of 3 is sufficient for convergence; while if the interface is placed at 500 m, a reflection level of 20 is required.
Fig. 5. Received power at 900 MHz in the Massif Central tunnel. RT is applied to generate initial source fields for the VPE and the source plane is set at 400 m. A reflection level of 14 is selected for the simulation of the RT subdomain.

TABLE II
COMPARISON OF ATTENUATION SLOPE, AVERAGE DEVIATION, AND EXECUTION TIME BETWEEN USING THE RT METHOD ALONE AND USING THE HYBRID MODEL

<table>
<thead>
<tr>
<th></th>
<th>RT alone (k=15)</th>
<th>RT alone (k=20)</th>
<th>RT alone (k=25)</th>
<th>Hybrid method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation slope (dB/km)*</td>
<td>14.5</td>
<td>11.4</td>
<td>10.2</td>
<td>8.1</td>
</tr>
<tr>
<td>Average deviation (dB)</td>
<td>7.9</td>
<td>6.1</td>
<td>5.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Execution time (s)</td>
<td>460.2</td>
<td>4655.0</td>
<td>49699.7</td>
<td>12.3</td>
</tr>
</tbody>
</table>

*The attenuation slope of the measured data is 8.5 dB/km.

Furthermore, the results of the received power generated by the hybrid model and by the RT method alone, varying the number of reflections per ray, are depicted in Fig. 5. It can be observed that the simulated results of the hybrid model are in better agreement with the measured data than the ones generated by using only RT. The results of applying RT alone did not converge even with a reflection level of 25, with which the simulation took more than 13 h performed on a workstation while on the contrary, the hybrid model took just around 12.3 s, corresponding to a speed up of 4041.

In Table II, the corresponding attenuation slope, average deviation, and execution time are compared, where the attenuation slope is again obtained via least-squares fitting to the data in the 0.5–2.5-km region. The average deviation is calculated by

$$\text{Average deviation (dB)} = \frac{1}{N} \sum_{1}^{N} \frac{|P_{\text{simulated}} - P_{\text{measured}}|}{N}$$

where $P_{\text{simulated}}$ is the simulated received power, $P_{\text{measured}}$ is the measured power data, and $N$ is the total number of sampling points. In the simulation, spatial discretization for the propagation direction is chosen as $\Delta s = 2$ m and $N$ is 1250.

IV. PROPAGATION MODEL FOR THE EDMONTON LIGHT RAIL TRANSPORTATION (LRT) SYSTEM

In this section, the hybrid method is applied to the propagation modeling of one section of the LRT system in Edmonton, Alberta, Canada. As illustrated in Fig. 6, the main part of this section is the railway station, where the existing obstructions such as the elevated platform, escalators, benches, ceilings, stairs, pillars, and railway tracks severely complicate the propagation model. The connecting sections, on the contrary, are simple and uniform tunnels. Hence, the proposed hybrid model, combining the versatility of RT and the computational efficiency of VPE, is best suited for such a heterogeneous railway network.

A. Model Extraction

In this section, the extraction of the geometry model for the RT subdomain is discussed. It can be seen from Fig. 6 that there are many geometric details complicating the specification of the input model. Moreover, it is known that, as with most simulation tools, accuracy of the output heavily depends on the quality and detail of the input parameters. However, in such railway stations, selecting the input parameters is not straightforward. It is hard to determine what level of details needs to be considered in the model and how these details should be modeled.

On one hand, as the computational cost increases exponentially with the number of surfaces in the model, the number of objects needs to be minimized; on the other hand, a sufficient level of detail is required to guarantee accuracy of simulation results. Therefore, the input geometry is extracted by systematically adding incremental details, as illustrated in Fig. 7, until there are minor or insignificant deviations in the numerical predictions.

The resulting deviations in the received power by incrementally adding the platform, the escalators, and the tracks, are depicted in Fig. 8. For this railway station, the platform and escalators are found to be the primary scattering objects that affect the propagation characteristics. More objects could be added, yet the deviations proved insignificant while unnecessarily increasing the computational cost.
Besides including the main objects, the wall properties need to be taken into account properly. As can be seen from the on-site image in Fig. 6, the walls present in this scenario mainly consist of large blocks of concrete, yet certain areas such as the bilateral walls of the station, as well as part of the ceilings are metallic instead of concrete. With these wall materials properly extracted, the agreement between the measurement and the RT prediction is improved significantly, as illustrated in Fig. 9.

### B. Simulated Results

In Fig. 10 (a) and Table III, the final modeled geometry is presented. At one end, the railway station is connected to a 40-m-long single-track tunnel; at the other end, it is followed with a 100-m-long dual-track tunnel; the railway station is 123 m long. The ceiling and bilateral walls of the railway station are treated as metal with $\varepsilon_r = 1$ and $\sigma_0 = 10^7$ S/m. All other parts are considered as concrete with $\varepsilon_r = 5$ and $\sigma_0 = 0.01$ S/m. The transmitter, a Yagi antenna operating at 2450 MHz, is placed at the beginning of the rectangular tunnel, 3.1 m in height and half a meter to the right wall. The measurement data are obtained by fixing the receiving equipment on a trolley which moves along the track and records the fields, as depicted in Fig. 10(b). There are two receivers, which are 3.1 m in height and 0.9 m apart, and the received power is calculated by taking the maximum power received by either of these two receivers.
To determine the location of the connecting interface, the total power density of all the electric fields within the $0^\circ$–$15^\circ$ and $15^\circ$–$90^\circ$ groups, respectively, are calculated. The variation of the power density weight of the two angle groups, as a function of propagation distance, is illustrated in Fig. 11. Since there are so many scattering objects in the station, the strength of the line-of-sight ray is much stronger than those which have undergone multiple reflections. As can be seen from the figure after just about 150 m, the 95% threshold is satisfied. Therefore, the connecting interface is placed right after the station area, at a distance of 164 m.

The simulated results are validated against measured data, provided by Thales Canada, in Fig. 12. RT with spatial discretization of $\Delta z = 1$ m for the propagation direction, and a reflection level of 10 is applied for the simulation of the station area, and VPE is reserved for the dual-track rectangular tunnel (from $z = 164$ m to $z = 263$ m). The spatial discretization for the VPE subdomain is chosen as $\Delta x = \Delta y = 0.1$ m, and $\Delta z = 1$ m. It can be observed from Fig. 12 that the simulated results have reasonably good agreement with the measured data, where the received powers are on the same level, and the profile of the simulated results captures the main maxima and nulls of

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### Table III: Geometrical Dimensions

<table>
<thead>
<tr>
<th></th>
<th>Width (m)</th>
<th>Height (m)</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-track tunnel</td>
<td>5.4</td>
<td>5.2</td>
<td>40</td>
</tr>
<tr>
<td>Dual-track tunnel</td>
<td>17.86</td>
<td>7.14</td>
<td>100</td>
</tr>
<tr>
<td>Railway station</td>
<td>17.86</td>
<td>7.14</td>
<td>123</td>
</tr>
<tr>
<td>Station platform</td>
<td>8.09</td>
<td>1.66</td>
<td>123</td>
</tr>
<tr>
<td>Escalators</td>
<td>4.53</td>
<td>5.48</td>
<td>7</td>
</tr>
<tr>
<td>Benches</td>
<td>2</td>
<td>0.8</td>
<td>15</td>
</tr>
</tbody>
</table>
Fig. 15. Received power at 2430 MHz on the open-air road. The whole simulated distance is 600 m. The spatial discretizations for the VPE subdomain are chosen as $\Delta x = \Delta y = 0.1$ m, and $\Delta z = 1$ m. (a) Interface: 10 m. (b) Interface: 15 m. (c) Interface: 20 m. (d) Interface: 25 m.

those of the measured data. These results further confirm the feasibility and validity of the proposed hybrid model.

V. OPEN-AIR GUIDEWAY

Another geometry that needs to be considered is the open-air guideway. There have been various techniques discussed in relevant literature to model wave propagation in such scenarios. In [28], statistical models are employed to evaluate the fading properties along “railway cuttings” in rural and suburban environments, where cuttings are used on uneven ground or hills to enable the train to get through.

RT has also been applied to predicting path loss in flat terrains and urban canyons [15]. However, the computational cost remains a problem in scenarios with slant cuttings or deep side walls. The hybrid model in this paper offers an alternative, efficient way to integrate this scenario in a comprehensive guideway simulation package. Moreover, RT can be used to generate initial conditions for VPE, enabling the modeling of actual antennas.

In this section, the hybrid model is tested with an open-air roadway in Whitby, ON, Canada. The on-site image of the roadway is shown in Fig. 13, and the polynomial fit of the elevation is illustrated in Fig. 14. RT with a reflection level of 2 is applied to generate the initial conditions for VPE. Within the VPE package, transparent boundary conditions [29] are applied to the open-air areas, and impedance boundary conditions are used for the ground. The cell sizes for the VPE subdomain are chosen as $\Delta x = \Delta y = 0.1$ m, and $\Delta z = 1$ m. The electrical parameters for the ground are set to $\varepsilon_r = 5.5$ and $\sigma_0 = 0.01$ S/m. The transmitter operating at 2430 MHz, is placed 1.55 m in height. The measurement data are obtained by fixing the receiving equipment (1.45 m from the ground to the center of the receiver) on a truck which moves along the road and records the fields along 600 m.

Notably, as the line-of-sight field components dominate in the open-air scenarios, a two-ray RT model is sufficient to generate the initial conditions, and the interface can be placed quite close to the transmitter. The received powers generated by placing the interface at various locations, at 10, 15, 20, and 25 m, are compared in Fig. 15. It can be observed that the profiles of the received power converge after the interface is placed at 20 m.

VI. CONCLUSION

The existing site-specific propagation models for tunnels and open-air guideways are either computationally intensive or measurement based or derived from oversimplifying the modeled geometry (such as the waveguide mode solvers for tunnel
propagation). This tradeoff between accuracy and efficiency can be overcome by hybridizing RT with VPE. This hybridization has been presented and analyzed in the present paper. As a result, a comprehensive framework for propagation prediction in an entire rail transportation system has been proposed. RT is reserved for geometrically complex and nonuniform parts of the channel, while VPE is applied whenever its fundamental assumptions are met. The proposed technique has been experimentally validated in tunnel, train station, and open-air geometries.

REFERENCES


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Prof. Sarris was an Associate Editor for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES (2009–2013) and the IEEE Microwave and Wireless Components Letters (2007–2009). He was the TPC Chair for the 2015 IEEE AP-S International Symposium on Antennas and Propagation and CNC/USNC Joint Meeting in Vancouver, BC, Canada. He was the recipient of the IEEE MTT-S Outstanding Young Engineer Award in 2013 and the Early Researcher Award from the Ontario Ministry for Research and Innovation in 2007. His students have received Paper Awards at the 2009 IEEE MTT-S International Microwave Symposium, the 2008 Applied Computational Electromagnetics Society Conference, and the 2008 and 2009 IEEE International Symposia on Antennas and Propagation.