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Ray tracing propagation modeling for future small-cell and indoor applications: a review of current techniques

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Abstract – Applied for the first time to mobile radio propagation modeling at the beginning of the nineties, ray tracing is now living a second youth. It is probably the best model to assist in the design and planning of future short range, mm-wave wireless systems, where the more limited propagation environment with respect to UHF frequencies, allows to overcome traditional high-CPU time limitations while the higher operating frequency makes ray-optics approximations less drastic and allows to achieve an unprecedented level of accuracy.

An overview of ray tracing propagation modeling is given in this paper, with a special attention to future prospects and applications. In particular, frontiers of ray-based propagation modeling such as extension to diffuse scattering, multidimensional channel characterization, MIMO capacity assessments and future applications such as real-time ray tracing are addressed in the paper with reference to the work recently carried out at the University of Bologna.

1. Introduction

Based on the ray-optic approximation of the propagating field [*Felsen and Marcuvitz*, 1973] and on the Uniform Theory of Diffraction [*Kouyoumjian and Pathak*, 1974], Ray Tracing (RT) models were initially applied to optical propagation problems. Only in the early nineties RT and its variants - ray launching, gaussian beam tracing etc. – have been applied to radio frequencies for field prediction in man-made environments such as the indoor and the urban environments [*Mckown and Hamilton*, 1991; *Rossi et al.*, 1991; *Seidel and Rappaport*, 1992].

Although their popularity has been increasing over the years, RT models haven't still achieved widespread application to mobile radio system design and planning problems mainly for their high

computation time and for the unavailability of detailed and reliable environment description databases. For these reasons a relevant effort within the scientific community addressed topics such as CPU time reduction through the decomposition of the 3D problem into one or more 2D problems [Liang and Bertoni, 1998; Rossi and Gabillet, 2002] or using techniques to increase the efficiency of the algorithm or to simplify the input database [Hoppe et al., 2003; Degli-Esposti et al., 2009a]. Things are probably going to change. With the advent of modern wideband, high speed mobile radio systems adopting MIMO, beamforming and other advanced transmission techniques, performance no longer depends only on signal-to-noise ratio (SNR) but also on the multi-dispersive characteristics of the radio channel. Thanks to their intrinsic capability to simulate multipath propagation, RT models seem therefore a good solution to provide an accurate, site-specific field prediction and a multidimensional characterization of radio propagation channel in the time, space and polarization domains [Liang and Bertoni, 1998; Athanasiadou et al., 2000; Kloch et al., 2001; Degli-Esposti et al., 2001, 2004; Rossi and Gabillet, 2002; Hoppe et al., 2003; Tila et al., 2003; Ng et al., 2007, Fuschini et al., 2008, Corre et al., 2009]. In order to fully achieve this potential, extensions to describe diffuse scattering phenomena have been recently developed to account for the signal scattered in other than the specular direction due to surface and volume details and irregularities of building walls [Degli-Esposti, 2001; Didascalou et al., 2003; Degli-Esposti et al., 2007a; Kwakernaat and Herben, 2010; Mani and Oestges, 2011; Mani et al., 2012; Lu et al., 2014a, Cocheril et al. 2006].

Future multi-gigabit wireless systems will mainly work at mm-wave frequencies due to the greater free bandwidth availability. Because of the very high through-wall attenuation, the propagation environment is relatively smaller at mm-waves compared to UHF frequencies, thus contributing to reduce both the complexity of the input digitized database and the computation effort. Moreover, the small wavelength compared to walls and objects dimensions makes the ray-optics approximation more acceptable, and RT results more accurate. At the same time, RT prediction capability may result more sensitive to the environmental clutter, since even small objects could

behave as good reflector at mm-waves, thus producing strong multipath contribution at the receiver. Such objects should be therefore identified and somehow included into the digital representation of the environment, which at the end won't be necessarily easier to be described if compared to lower frequency. Hopefully, accurate digitized maps of outdoor and even indoor environments as well as cheap computation power will become more and more readily available in the next future.

All considered RT models seem to be the good candidates to assist in the design, planning and optimization of next generation wireless systems. RT models have been recently used to derive mm-wave path-loss models [Jacob *et al.*, 2013; Ghaddar *et al.*, 2013] to perform multidimensional channel characterization, often in combination with measurements [Peter *et al.*, 2007; Dupleich *et al.*, 2014; Gustafson *et al.*, 2014; Kazemi *et al.*, 2012; Rasekh *et al.*, 2009; Gemc *et al.*, 2012], or to design the radio interface of 5G mobile radio systems [Larew *et al.*, 2013; Fugen *et al.*, 2006]. Other recent applications include the use of RT to characterize the THz propagation channel [Priebe *et al.*, 2013; Fugen *et al.*, 2006] or to assist indoor localization techniques [Laaraiedh *et al.*, 2012].

This article gives an overview of the main applications of RT to the study, design and planning of future short-range, multi-gigabit wireless systems. State-of-the art RT techniques for short-range propagation simulation are described in section 2 with a special focus on the full 3D indoor RT model developed at the University of Bologna in the last years. The multidimensional prediction potential of RT is illustrated in section 3, while some of the most important present and future applications are shown in section 4. Finally, section 5 concludes the paper.

2. State of the art of RT techniques for radio propagation modeling

This section illustrates the main issues related to ray tracing deterministic propagation modeling with reference to the full three-dimensional (3D) RT tool developed at the University of Bologna named 3DScat; beside "standard" interactions such as reflection/diffraction/transmission adopting an "image-RT approach" (see section 2.1), diffuse scattering (DS) is taken into account based on

80 the “effective roughness” (ER) approach [*Degli-Esposti et al.*, 2007a], which is embedded into the
81 RT model according to a “ray launching solution” (see section 2.2). The ER model allows simply
82 but effectively describing phenomena related to the roughness of the walls, or to surface/volume
83 irregularities that cannot be modeled in the input database (see section 3.2).

84 With respect to a previous work [*Degli-Esposti et al.*, 2004], mainly oriented to outdoor
85 scenarios, the model described here after is particularly fit to short-range propagation studies for
86 small-cell and indoor applications. For the sake of completeness also the “Ray Launching
87 approach” to RT is described in sub-section 2.3 at the end of in this section, while parallelization
88 techniques to speed up computation are shortly addressed in sub-section 2.4.

89 Regardless of the algorithm approach, the RT engine requires to be fed by a detailed description
90 of the geometrical and electromagnetic properties of every object inside the simulation domain.
91 Objects are mainly walls, but they can represent also pieces of furnishings or any other architectural
92 element or urban furniture that can be present inside or outside buildings. For the sake of simplicity,
93 each object is usually assumed to be made of a finite number of flat-surface slab elements. For each
94 element, the vertex coordinates, the thickness, the complex permittivity and the parameters of the
95 diffuse scattering model must be specified in the input files. The 3D polarimetric antenna radiation
96 files must be also inputted in the RT program.

97 2.1 *The visibility tree*

98 First of all, the algorithm arranges all the objects in a database containing all the visibility
99 relationships among them, usually known as “visibility tree”. Starting from the root of the tree,
100 corresponding to the transmitter (Tx), the visibility tree is built according to a recursive procedure:
101 the first layer contain all the objects (or part of them) that can be seen directly from the Tx; more in
102 general, the n-th layer contain the objects that can be seen from those belonging to the (n-1)-th
103 layer. In particular, objects are stored in the tree by means of proper “virtual transmitter” (VTx). For
104 example, the first-order reflection VTx is defined as the symmetric point (image) of the real Tx with
105 respect to the surface plane, according to the “Image Ray Tracing” approach [*Bertoni*, 2000].

106 During the building of the visibility tree, only the objects falling in the visibility region of each VTx
107 are pre-selected for the inclusion in the database, in order to reduce the computation time.

108 The next step is the determination of visibility, i.e. the selection of the rays that satisfy the
109 requirements, – e.g. number of interactions less than or equal to the maximum number requested at
110 input – and the exact determination of the interaction points.

111 The visibility is performed through the Binary Space Partitioning (BSP) algorithm [*Glassner et*
112 *al.* 1984; *Kaplan*, 1985]. Using BSP, a ray casting is done from the generic VTx to each receiver
113 (Rx): the number of hit objects is then determined. If the number of hit objects is higher than the
114 number of allowed transmissions, or at least one of the objects is set as not penetrable, the current
115 ray is discarded. Otherwise, the tracing procedure for the current ray is completed by determining
116 the exact ray path (reflection/diffraction points), and the field computation is then performed. It is
117 worth noticing that the visibility procedure can be performed in parallel on different cores of multi-
118 core processors or general purpose graphical processing units (GP-GPU) commonly present in
119 modern computers and workstation, with considerable reduction in computation time compared to
120 the past years, as discussed in section 2.4.

121 2.2 *The alternative approach to image RT: Ray Launching*

122 Ray Launching algorithms are based on rays launched from the transmitter with a discrete angle
123 increment. Each ray is representative of a ray tube of given angular aperture, and thus the field is
124 assumed constant over the cross section of the ray tube. Therefore, differently from the image RT
125 algorithm, an angular/spatial discretization is assumed, which limits prediction accuracy. As a
126 compensation, ray launching is more CPU-time efficient than image-RT algorithms for prediction
127 over vast areas or volumes.

128 Given a spherical reference system with angular coordinates θ and ϕ a test ray scanning from
129 $\theta=0^\circ$ to $\theta=180^\circ$ and from $\phi=0^\circ$ to $\phi=360^\circ$ with a pre-set angular separation is launched from the
130 Tx, is followed determining interaction points (reflections and diffractions over obstacles) and the
131 corresponding interaction coefficients, and the rays arriving at the Rx with a significant level of

132 power are at last identified. To determine if a transmitted ray reaches a Rx it is necessary to
133 construct a reception circle around the Rx of proper size [B. S. Lee et al., 2001]. Ray launching
134 processes can be implemented simultaneously from both the Tx and the Rx sides to increase
135 accuracy and efficiency [Zhu et al., 2012].

136 Despite the lower computational complexity compared to image-RT algorithms, the inherent
137 discretization causes rays to “miss” Rx locations when they propagate and disperse increasing their
138 spatial separation. Ray splitting can be a solution: more rays are introduced in order to reduce the
139 angular separation [Lai et al., 2009]. Also, proper angular discretization methods based on
140 polygonal shapes can be adopted to overcome resolution limitations [Rose et al., 2014].

141 With reference to the 3DScat RT tool mainly addressed in this work, ray launching is exploited
142 to implement DS, as shortly explained in the following section.

143 2.3 Diffuse scattering modeling

144 The adopted ER model requires the proper subdivision of each surface element in smaller “tiles”.
145 Such tiles are pre-determined at the beginning of the RT procedure, using a ray-launching approach
146 . Several rays are launched from each Tx/Rx according to a pre-set angular discretization, and the
147 scattering tiles are then identified as the intersection between the launched beams and the objects
148 inside the scenario; the area of each tile is related to the angular discretization and to the distance
149 from the ray source. A new VTx is then placed at the center of each scattering tile, and the visibility
150 process is then repeated as if it were a new real transmitter. The scattering objects are divided into 3
151 categories:

- 152 ▪ “Local” scatterers at Tx side, i.e. scattering objects directly visible from the transmitter.
- 153 ▪ “Local” scatterers at Rx side, i.e. scattering objects directly visible from the receiver.
- 154 ▪ “Far” scatterers, i.e. scattering objects not directly visible from Tx/Rx.

155 Of course, the inclusion of DS in the RT model determines a considerable increase of the
156 computational burden, due to the much higher number of rays to be tracked by the algorithm. For
157 this reason, in [Degli-Esposti et al., 2009b] a new method was derived in order to compute the

overall power-angle distribution of a single wall, taking into account the effect of the different “tiles” with a simple analytical formula. With this approach, the analytical power-angle profile (PAP) of diffuse scattering is summed to the PAP of the “coherent” interactions (reflections, diffractions), without the need for tracing scattered rays. Diffuse scattering can be therefore embedded into the RT tool preserving its intrinsic, distributed nature and giving more realistic results (see also next section), but limiting at the same time the required computational burden.

The prediction performance of RT models obviously depends on several factors, including the electromagnetic parameters of the walls/objects, (as highlighted in section 3.3) and the parameters of the DS model. With regard to the latter, an extensive validation and parameterization has been done in the recent years by means of experimental investigations in several types of environment. The main parameters of the ER model are the scattering coefficient S (with $0 < S < 1$), directly related to the overall amount of power scattered at the expense of specular reflection, and the scattering radiation pattern, describing how the scattered power is distributed in space. The ER model is *physically sound*, because the scattered power due to wall irregularities is subtracted from specular reflection, introducing a proper reflection reduction factor $R = \sqrt{1 - S^2}$ (with $0 < R < 1$), thus preserving overall power balance [Degli-Esposti et al., 2007a]. According to [Degli-Esposti et al., 2007a, Mani et al., 2011] S can vary between 0.2 and 0.4 in rural environments, while higher values, up to 0.6, can be reached in scenarios with complex building structures [Vitucci et al., 2012]. As for the scattering pattern, recent studies have shown that satisfactory results can be obtained by assuming a single-lobe pattern centred on the direction of the specular reflection; in particular, the power density of DS is proportional to:

$$S(\psi_R) = \left(\frac{1 + \cos \psi_R}{2} \right)^\alpha \quad (1)$$

where ψ_R is the angle between the specular reflection direction and the scattering direction, and α is a coefficient that sets the width of the scattering lobe. Typical values of α range between 2 and 4

182 [Degli-Esposti et al., 2007a; Mani et al., 2011], allowing to obtain good prediction accuracy with
183 respect to narrowband and wideband measurement data.

184 In [Degli-Esposti et al., 2011; Vitucci et al., 2012] an additional parameter, named K_{xpol} , is
185 introduced in the ER model in order to somehow take into account the depolarizing effect due to
186 DS. With reference to the basic, vertical and horizontal linear polarization states, $K_{\text{xpol}} = 0$ means
187 that the scattered field has the same polarization of specular reflection; when it is equal to 0.5, the
188 power is equally split between the co-polar and cross-polar components, and for $K_{\text{xpol}} = 1$ the power
189 would be totally transferred to the cross-polar component. K_{xpol} usually ranges between 0 and 0.2 in
190 outdoor environment [Vitucci et al., 2012], where therefore the polarization of the incident wave
191 tends to be preserved. On the contrary, values of K_{xpol} close to 0.5 are achieved in typical office and
192 laboratory environments [Mani et al., 2014], meaning that the diffuse scattering component tends to
193 be completely depolarized in complex indoor scenarios.

194 2.4 Using the graphics processing units

195 Although the high computing time is still one of the weak points of RT algorithms, with the
196 rapid development of graphics hardware in the recent years new solutions have been proposed to
197 exploit the high computing power and large memory bandwidth of GP-GPUs. Specific frameworks
198 for the GP-GPU have been developed such as the Compute Unified Device Architecture (CUDA)
199 by NVIDIA [NVIDIA corporation, 2014].

200 Due to the massive parallelization capabilities of GP-GPUs, considerable reduction in
201 computation time of Ray Tracing/Ray Launching simulations can be obtained especially when the
202 GPU-based implementation is combined with efficient shooting and bouncing ray algorithms like
203 BSP or kd-tree [Catrein et al., 2007; Rich et al., 2010]. Of course the algorithm code must be
204 properly modified or interfaced to allow proper parallelization on the GPU.

205 In [Rich et al., 2010] speedups of 2.5X for over-rooftop predictions, and up to 160X for
206 predictions in urban street canyons are reported, with respect to simulations carried out with a
207 standard Ray Launching algorithm, in a typical urban environment. In full-3D ray/tube tracing

208 simulations, average reduction factors of 30 times in computation time can be obtained, as reported
209 in [Yubo *et al.*, 2010].

210 **3. Multidimensional prediction capability**

211 The quality of service of a wireless systems always depends on many factors, and the received
212 signal strength has traditionally represented one of the most crucial among them [Parsons, 2000].
213 For a long time, system planning has basically aimed at pursuing a satisfactory coverage level, and
214 propagation models were mainly required to provide satisfactory narrowband, path-loss (PL)
215 predictions.

216 In this context, ray based tools have been commonly discarded in favour of simpler and ready-to-
217 use statistical/empirical models such as the Hata model [1980].

218 The trend will probably change with the advent of future generation wireless systems, whose
219 design and deployment will greatly benefit from wideband and multi-dimensional radio channel
220 modelling capability.

221 In fact, the effectiveness of technical solutions such as multi-antenna arrangements, already
222 included in the 802.11ad and 4G (LTE) standards and definitely considered also for future 5G
223 systems at millimeter-wave [Rappaport *et al.*, 2013; Roh *et al.*, 2014], is still affected by the
224 received signal intensity but also by others parameters related to the multipath nature of the radio
225 channel (e.g. angle spread, polarimetric properties, etc.). Enhanced prediction capabilities, also
226 extended to the so-called multidimensional channel characterization [Fuschini *et al.*, 2008], will
227 become therefore more important, if not necessary, in the near future.

228 Since the ray approach is naturally fit to model multipath propagation and to provide a complete
229 channel estimation, RT models are therefore gaining consideration, and their use is becoming more
230 and more familiar within the scientific community to perform multidimensional channel
231 characterization at mm-wave and THz frequencies [Dupleich *et al.*, 2014; Priebe *et al.*, 2013], or to
232 support the planning of the incoming wireless networks [Larew *et al.*, 2013].

233 Besides, the ongoing idea of exploiting the underutilized millimeter-wave bands to meet the
234 request for higher data-rates may also further spur the use of ray tracing techniques, especially
235 applied to indoor scenarios, where the large penetration losses might restrict the simulation area
236 basically to a single room, thus strongly contributing to decrease the computational effort.

237 Some of the main issues related to the prediction capabilities of the RT-based radio channel
238 models are further highlighted and discussed in the following sub-sections, mainly on the base of
239 comparison with measurements.

240 *3.1 MIMO parameters prediction accuracy*

241 The capability of RT models to provide a full radio channel characterization is for instance
242 investigated through the comparison shown in Fig. 1 and related to a 2×2 MIMO link at the
243 frequency of 858 MHz, deployed in a typical, modern indoor office environment with internal walls
244 made of plasterboard. In particular, measurements and simulations have been compared with the Rx
245 unit placed in 10 different positions along a linear route in a corridor, with a spacing of about 7λ
246 between the Rx positions, and the Tx placed at about one third of the corridor length. Two omni-
247 directional antennas with $\lambda/2$ spacing have been used at both the link ends. Moreover, in order to
248 get local averages, both measurement and simulation data have been averaged on a 4 x 4 point grid
249 centered on each measurement position, with a grid step of $0.66\lambda \times 0.5\lambda$. Further details about the
250 experimental setup and the considered scenario can be found in [Vitucci *et al.*, 2014].

251 The result clearly shows that deterministic propagation modelling based on ray tracing simulations
252 can provide satisfactory predictions not only limited to the received power values (Fig. 1a) but also
253 extended to other, specific parameters such as the Condition Number (CN) [Clerck and Oestges,
254 2013] considered in Fig. 1b. In a MIMO system, CN is defined as the imbalance between the
255 maximum and the minimum singular values of the channel matrix $\mathbf{H}$, and it is strictly related to the
256 theoretical capacity of the MIMO link [Vitucci *et al.*, 2014].

257 The CN estimation shown in Fig. 1b represents just an example of the RT potential to investigate
 258 system parameters strictly related to radio propagation. Generally speaking, the whole channel
 259 matrix can be of course evaluated by means of the RT approach, and this may then allow the
 260 computation of many different parameters in addition to the CN. For instance, the (multipath)
 261 richness vector $\mathbf{N}$ can be also achieved, which represent a more general parameter than CN for
 262 higher order MIMO [Clerckx and Oestges, 2013]. Another example of prediction of MIMO
 263 parameters will be shown in the next subsection, with reference to the assessment of MIMO
 264 capacity in a small-cell outdoor scenario.

265 It is worth noticing that CN, $\mathbf{N}$ and MIMO capacity are “coherent parameters”, i.e. their
 266 evaluation requires the assessment of the whole channel matrix $\mathbf{H}$, including the amplitude and the
 267 phase distributions of the multipath components. Simple narrowband models such as PL formulas
 268 are therefore completely unfit to their reliable prediction.

269 Although RT prediction is intrinsically site specific, it can be nevertheless exploited to provide a
 270 statistical characterization of different, representative scenarios. In fact, multiple RT runs can be
 271 carried out for a given environment, and the results can be collected and regarded as different,
 272 possible realizations of the same random process. Therefore, statistical parameters such as mean
 273 values, std. deviations, cumulative distribution functions (CDF), correlations can be easily
 274 computed. For instance, with reference to a MIMO system affected by correlated Rayleigh or Rice
 275 fading, the RT-based statistical characterization can include the Rice factor (K) and the complex
 276 correlation coefficients between the elements of the channel matrix. Such parameters have provide a
 277 synthetic description of the main characteristics of small-scale fading, which are of particular
 278 importance for evaluating the performance of a MIMO system in a given type of environment.
 279 [Clerckx and Oestges, 2013]. Table 1 shows a comparison of measured and simulated Rice Factor,
 280 and of the mean values and standard deviations of the correlation coefficients at Tx side (ρ_{11-12} , ρ_{21-}
 281 $_{22}$), at Rx side (ρ_{11-21} , ρ_{12-22}), and between cross-channels (diagonal correlations, ρ_{11-22} , ρ_{12-21}), being

282 $\mathbf{H} = \{h_{ij}\}_{i=1,2}^{j=1,2}$ the channel matrix of the indoor 2x2 MIMO link previously referred to at the
 283 beginning of the sub-section. For example, the complex correlation coefficient at Tx side can be
 284 defined as:

$$285 \quad \rho_t|_{n=1,2} = \rho|_{11-12,21-22} = \frac{E[h_{n1}h_{n2}^*]}{\sqrt{E[|h_{n1}|^2]E[|h_{n2}|^2]}}$$

286 which is the correlation between channels originating from transmit antenna elements 1 and 2 and
 287 arriving at the same receive antenna n . Similar definitions can be obtained for the Rx-side
 288 correlation and the diagonal correlation.

289 According to the statistical characterization of the main link parameters achieved through the RT
 290 model, different realizations of the channel matrix can be then randomly generated, which can be in
 291 general used in system level simulation for system design applications [Rashid-Farrokhi et al.,
 292 2000, Clerckx and Oestges, 2013].

293 3.2 The role of diffuse scattering in RT prediction

294 When a radio wave impinges on a building wall, the field is scattered in a wide range of
 295 directions, due to rough surfaces, decorative masonry, internal irregularities (such as inner
 296 reinforcements, power lines, heating pipes, etc.) and external irregularities (windows, rain pipes,
 297 windowsills, balconies, etc. for outer walls; doors, wall cupboards, picture frames, etc. for inner
 298 walls).

299 In order to effectively account for the actual backscattering pattern, rigorous methods (finite
 300 elements, finite-difference time-domain - FDTD, method of moments - MoM) might be used but
 301 they are often excessively time consuming. However, numerical methods (FDTD, MoM) have been
 302 recently and effectively combined with RT techniques to account for the scattering properties of
 303 small objects in indoor environment [Reynaud et al. 2006] or to take into account scattering
 304 mechanisms from building facades and corners [Ouattara et al. 2011].

305 Moreover, the modeling of scattering from real walls can be hardly regarded as a deterministic
306 problem. Irregularities are usually not reported in databases to limit the amount of data storage or
307 simply because they are unknown at all.

308 As already mentioned in the previous section, a simple but effective way to extend RT prediction
309 to diffuse scattering is represented by the ER approach, whose effectiveness has been proved in
310 recent years, since the introduction of DS through the ER model can considerably improve the
311 multi-dimensional prediction capabilities of the ray models, in particular with regard to the
312 wideband and angular characteristics of the received radio signal [*Fuschini et al.*, 2008, *Mani et al.*,
313 2012], as well as the effect of cross-polarization on the performance of dual-polarized MIMO
314 systems [*Degli-Esposti et al.*, 2007b, *Vitucci et al.*, 2008, *Degli Esposti et al.*, 2011].

315 The importance of DS in RT prediction is for instance highlighted in Fig. 2, where the
316 complementary CDF of the MIMO capacity evaluated in a “Manhattan-like” propagation scenario
317 with and without scattering is compared to some experimental data gathered during a measurement
318 campaign carried out in Manhattan [*Vitucci et al.*, 2006; *Chizik et al.*, 2003]. In this case,
319 measurements were taken using a narrowband channel sounder at 2.11 GHz with a dual-polarized
320 8-element linear array at Tx side, and a dual-polarized 8-element planar array at the Rx mobile unit,
321 therefore forming an 8x8 dual polarized MIMO system. The base array was placed at a height of
322 100 m facing east at the corner of 35th Street and 8th Avenue in the dense urban environment of
323 midtown Manhattan, and the terminal array was mounted on the side of a van, at a height of 1.5 m.
324 Transmit power was 23 dBm per element. Some more details about the measurement campaign can
325 be found in [*Chizik et al.*, 2003]. The same antenna arrangement has been given in input to RT
326 simulations, while only the main geometrical characteristics of the scenario (width of the streets,
327 average height of buildings) have been reproduced, without taking into account a detailed
328 description of the buildings. As shown in Fig. 2, the prediction achieved neglecting diffuse
329 scattering is clearly rather poor, whereas a much more satisfactory comparison is achieved if the ER
330 model is embedded into the RT simulator, thus confirming the validity of the “hybrid” approach

331 based on the combination of deterministic modeling (coherent interactions mechanisms) and
332 statistical modeling (diffuse scattering, through the ER approach).

333 Similar results are expected in small-cell indoor environment, especially in cases where the Tx
334 and the Rx are in non line of sight (NLOS) and the rays undergoing just coherent interactions
335 (reflections, diffraction and transmission) are suppressed compared to those undergoing DS (for
336 example, Tx and Rx placed at the opposite ends of a corridor with some 90 degree bends in
337 between).

338 In order to achieve an accurate prediction, the size of the tiles providing the diffuse scattering
339 contributions shouldn't be too large. According to the ER approach, scattering from a finite surface
340 element is regarded as a "diffuse phenomenon", i.e. it cannot be reduced to few contributions
341 coming from specific interaction points (like reflection, diffraction and transmission) but on the
342 contrary it rather springs out from the whole surface illuminated by the incoming wave. According
343 to this "distributed nature", the smaller the tile size (i.e. the finer the angular discretization
344 considered for the Ray Launching procedure), the more reliable is the modeling of the scattered
345 contributions at the Rx. Of course, a small tile size corresponds to a large number of tiles, and this
346 may strongly increase the computation time requested by the RT simulation. As discussed at the end
347 of section 2, this issue can be partly handled resorting to the analytical approach to DS model
348 introduced in [Degli-Esposti *et al.*, 2009b].

349 The convenience of a reduced tile size is evident in Figs. 3-5 (drawn from [Degli-Esposti *et al.*,
350 2009b]), where the power-angle spectrum (PAS) measured along the route 4 in central Helsinki
351 represented in the following Fig. 6 is compared to the prediction provided by the RT model
352 described in section 2. Measurements were taken using a wideband channel sounder at 5.3 GHz,
353 with a planar array of 16 dual-polarized elements at Tx side, mounted on a 10 m high pole, and a
354 hemispherical array of 21 dual-polarized elements at the Rx unit. The Rx positions along
355 measurement route 4 were at a distance ranging from 150 to 240 m from the Tx, the Rx was at a
356 height of 1.6 m above ground level, and the Tx power was 37 dBm [Degli-Esposti *et al.*, 2011].

PAS to be compared with RT simulation were extracted from the measurement data with a high resolution estimation algorithm based on the SAGE method [Fessler and Hero, 1994]. Results show that in the considered environment a finer angular discretization (Fig. 5) allows a better prediction than a rougher subdivision in tiles of the scattering surfaces (Fig. 4), therefore giving a PAS more similar to the one extracted from measurements, shown in Fig. 3.

3.3 Sensitivity of RT prediction to environment modelling

A major concern about RT prediction models is due to the need for a very detailed and precise description of the environment; the rougher and the more incorrect the representation of the simulation scenario stored in the input database(s), the poorer the corresponding prediction accuracy. Of course, the environment description includes both geometrical and electromagnetic issues. The geometrical aspects concern number, shape, dimension and position of all the objects interacting with the propagating field; in case of outdoor simulation over an hilly area, the terrain profile must be also properly taken into account. The necessary geometrical information have been traditionally acquired through some automatic procedures (such as aerophotogrammetry), which could be rather expensive. Nevertheless, the availability of open access, digitized databases on the web is quickly increasing, and this might suggest that the acquisition of the geometrical data should become easier and cheaper in the next future.

However, irrespective of the acquisition procedure, some errors in the geometrical description of the simulation environment are practically unavoidable. For instance, with reference to urban digital maps for outdoor prediction, it is difficult to have a building databases with position accuracy better than 0.5 m, which is often on the order or greater than the wavelength [Bertoni, 2000]; building heights are often even less accurate, due to the shape approximation of the rooftops.

The impact of such inaccuracies in the digital maps should be of course evaluated case by case; according to the study carried out in [Rizk et al., 2000] related to ray-tracing based prediction in urban microcells, errors in the walls position within ± 2 m in the 95% of cases correspond to an increase in the std. deviation of the prediction error equal to 1 dB. The same result can be achieved

383 from inaccuracies in the digital database in which 95% of building vertices are within ± 1 m from
384 their actual position.

385 The electromagnetic aspects relates to the evaluation of the electromagnetic properties (often
386 limited to the electrical permittivity ϵ_R and the conductivity σ) of the constitutive materials at the
387 frequency of interest. The usual presence of compound materials as well as of possible unknown,
388 ‘hidden’ unhomogeneities (such as pipes and cables buried inside building walls, for instance) may
389 represent a serious hindrance to a reliable assessment, and therefore a limit to the final prediction
390 accuracy.

391 This last aspect is considered in Fig. 7, where the measured and the simulated values of delay
392 spread (σ_ξ) are compared in a large indoor environment, represented by an exhibition hall of the
393 Messe Berlin. A vector network analyzer having its ports connected to two biconical antennas by
394 means of coaxial cables has been used to collect several values of the S_{21} parameter in the
395 frequency range from 300 MHz to 3 GHz and over a grid of locations deployed over the whole area
396 [Sczyslo *et al.*, 2012].

397 The σ_ξ prediction achieved with standard electromagnetic (EM) parameters ($\epsilon_R \approx 5$, $\sigma \approx 1e-2$) is
398 unsatisfactory, since the delay spread values are strongly underestimated by the RT simulation.

399 In order to understand the reasons of such a problem, the actual structure of the exhibition hall
400 has been investigated, finding out that the floor and the ceiling included significant metal structures:
401 a reinforcing metal mesh in the former (as shown in Fig. 8) and complex tubular metal structures in
402 the latter, which is actually a suspended ceiling with an inter-space. Since a high reflectivity from
403 both the floor and the ceiling should be therefore expected due to such metal core, their
404 conductivity was therefore increased up to 10^6 [S/m], which may be somehow representative for
405 many real metals [Balanis, 1989]. As clearly shown in Fig. 7, this improvement of the EM
406 properties of the involved materials yields a dramatic increase in the prediction accuracy.

407 The strong sensitivity of RT models to the accuracy in the environment description can represent
408 a problem at millimeter waves, since only a few studies on the characterization of the EM properties
409 of materials in the millimeter-wave bands are available in the scientific literature to date [*Lu et al.*,
410 2014b; *Cuinas et al.*, 2001].

411 **4. Advanced applications of Ray Tracing**

412 A number of advanced applications of RT going beyond field prediction for radio planning are
413 envisioned for the next future. In order to cope with the increasing demand of high throughput in
414 wireless communication systems, advanced radio transmission and antenna techniques, such as
415 MIMO and beamforming have recently been proposed together with the exploitation of new
416 bandwidth at millimeter-wave frequencies. Although the propagation environment is smaller at
417 mm-wave frequencies compared to UHF due to the limited through-wall penetration, and therefore
418 RT application potentially faster and easier, a new problem may arise: even small objects not
419 present in the environment database can become good reflectors at mm-waves due to the small
420 wavelength and therefore could give important contributions, as highlighted in [*Dupleich et al.*,
421 2014; *Gustafson et al.*, 2014]. One possible solution to this problem is the description of such
422 common-use objects within the RT algorithm (e.g. neon lamp reflectors, computer monitors, etc.) as
423 point-scatterers with a typical bistatic radar cross-section that could be determined through
424 experimental characterization in anechoic room. This solution however will also require the
425 knowledge of the presence and of the position of such objects, and therefore will pose new
426 challenges to environment mapping techniques.

427 A second option may refer to the ER model, already discusses in the previous sections, that
428 could be somehow extended to statistically account for scattering from the indoor clutter. This
429 solution wouldn't require the inclusion of small scattering objects in the input database; however,
430 the possibility of effectively replacing small scatterers usually present in indoor scenarios with an

431 effective roughness attributed to the room walls or to other, larger objects is something that needs
432 further investigations.

433 Present and future mm-wave applications include gigabit-wireless indoor connectivity [*Hansen*,
434 2011], as well as mm-wave front-hauling and back-hauling systems [*Rappaport et al.*, 2013;
435 *Coldrey et al.*, 2012]. The small wavelength of mm-waves allows the implementation of large
436 MIMO antenna to put into action pencil beamforming techniques using very narrow beam for high
437 spatial-spectrum reuse and signal-to-interference ratios.

438 As already argued, the design and the optimization of systems adopting such techniques may
439 require a thorough knowledge of the directional characteristics of the propagation channel, and RT
440 represents the best tool for this task. Moreover, the availability of low-cost computation power,
441 detailed 3D digital building databases and accurate techniques for the localization of the mobile
442 terminals in future systems, will probably encourage the use of RT models not only “off-line” to
443 assist in the system design and deployment phase, but also embedded into the system for on-line,
444 real-time channel prediction to help estimate the channel state information (CSI), thus reducing the
445 need of complex and time-consuming channel estimation techniques based on the transmission of
446 training-sequences and CSI feedback to the Tx.

447 Future possible applications include embedded, Real-Time applications such as RT-assisted
448 channel estimation for implementing optimal beamforming or beam-switching techniques for
449 mobile back-hauling (MBH, also called mobile front hauling) systems or for future multi-gigabit
450 wireless applications. Other techniques where RT might find successful application in the near
451 future are radio frequency pattern matching (RFPM) or fingerprinting radio localization techniques.
452 Such techniques are briefly illustrated below.

453 4.1 *Ray-tracing for MBH*

454 MBH systems are being designed and deployed to connect small-cell overlay base stations
455 installed along streets with hubs usually located on building roofs next to existing macrocellular

456 sites [Coldrey *et al.*, 2012]. Due to the greater available bandwidth, MBH system will be mainly
457 allocated at millimeter wave frequencies and will be equipped with very directive antennas to
458 maximize the SNR and minimize interference. Such directive antennas will be realized through
459 adaptive arrays to allow real-time, autonomous beam-steering capabilities, or simply will be pointed
460 by expert personnel during installation. Anyway, the presence of a path in Line of Sight (LOS)
461 cannot be always guaranteed in such applications. Therefore a thorough analysis of the LOS
462 probability and of the power angle distribution (PAD) of the signal in reference urban layouts is
463 mandatory to properly design and/or install MBH systems.

464 In [Barbiroli *et al.*, 2014] the statistical PAD at the receiver has been evaluated with reference to
465 the radial Tx-Rx direction through 3D ray-tracing simulations. In Fig. 9 the PAD in ‘section (2)’ of
466 the route GH (NLOS street canyon, see Fig. 6) with respect to the radial direction is evaluated. It is
467 evident from Fig. 9 that the strongest path does not correspond to the radial direction, neither to the
468 street direction from H to G, but comes from back scattering off buildings on the opposite street
469 side with respect to the Tx, where upper building sections are directly illuminated by the Tx.

470 Results of the study show that the LOS probability is very small in dense urban environment,
471 thus directive-antenna and beamforming techniques cannot rely simply on the position information
472 of the radio terminals to maximize the power-budget and guarantee reliable transmission. The
473 analysis of the PAD distribution for different receivers locations show that diffuse scattering plays a
474 key role here. Moreover abrupt changes in both PAD and multipath structure are found, especially
475 in the vicinity of street intersections. These results can help implement optimal beamforming
476 techniques for MBH systems, and could help the deployment of small-cell base stations in next
477 generation mobile networks.

478 4.2 *Real-time Ray-tracing for assisted beamforming.*

479 In this section a preliminary investigation is carried out to assess the potential of RT-assisted
480 beamforming in a next generation 60 GHz indoor radio access system where the access point (AP)

481 is equipped with a planar 2×8 or 12×12 antennas antenna array, while the user's antenna is assumed
482 omnidirectional. The considered indoor environment is shown in Fig. 10, where user and interferer
483 have been placed in different locations on the 24-node grid, and the AP is placed in the corridor.
484 User and interferer can simultaneously communicate thanks to space division. Also interference
485 from the upper and lower floor, each one with two active communications is considered.

486 For each communication, if the location of the mobile user is known, the simplest solution,
487 which doesn't require complex CSI estimation procedures, is to steer the beam toward the mobile
488 direction. Unfortunately, the LOS path is often blocked by walls and objects, e.g. the metal
489 cupboard highlighted in black in Fig. 10.

490 An alternative solution is to determine the M strongest paths ($M=6$ has been chosen in the
491 following) through RT simulation and steer the beam toward the one of them yielding the best
492 carrier-to-interference-plus-noise ratio (SINR) at the mobile.

493 Both solutions have been evaluated through simulation, using the ray tracing model described in
494 Section 2 with 2 reflections, 1 diffuse scattering interaction and of course taking into account
495 through-wall transmission loss.

496 Simulation results of Fig. 11 show that the RT-assisted beamforming techniques allows an
497 increase of SINR up to 25 dB in obstructed locations (namely locations # 2, 6, 7, 10, 15, 17) using
498 the 2×8 array, and the increase is even greater for the 12×12 array. The use of an omnidirectional
499 antenna at the AP (SISO case, just for reference here) of course yields a very poor SINR as no space
500 division to separate user and interferers is possible in this case.

501 Of course real-life implementation of RT-assisted beamforming will suffer performance
502 degradation with respect to what shown here due to inaccuracies in the RT prediction. This, and
503 other aspects will be object of further, more extensive investigations.

504 *4.3 Ray-tracing-assisted localization.*

505 Radio localization is a very valuable service already available in today's systems [*Liu et al.*
506 2007]. Present localization solutions however, such as those planned for the Long Term Evolution
507 standard are quite limited in terms of indoor coverage and accuracy due to the limited indoor
508 penetration of GPS and outdoor mobile radio signals [*3GPP TS 36.305*].

509 In principle, radio localisation techniques are based on the detection of the angle-of-arrival
510 (AOA), of the time-of-arrival (TOA), or of the received signal strength (RSS). While the first two
511 heavily depends on the specific technology and transmission technique, RSS-based localization
512 relies only on the received power measurement, a parameter easily accessible in almost all radio
513 equipments, including many current standards, such as WiFi [*Pahlavan et al.*, 2002]. A drawback of
514 RSS-based localization is that a complete map of RSS in the environment has to be provided by
515 calibration measurements. Alternatively, deterministic propagation models may be employed, and
516 RT is one of the best candidates for this task. The accuracy achievable with RSS-based localization
517 is however poor for typical access point deployments [*Shi and Wigren*, 2009]. More advanced
518 finger printing or RT-based pattern recognition methods have been proposed taking into account
519 AOA, RSS, Doppler, TOA, etc. [*Hatami et al.*, 2006; *Papakostantinou et al.*, 2009; *Pahlavan et*
520 *al.*, 2006; *Giorgetti and Chiani*, 2013; *Dardari et al.*, 2009; *Kuang et al.*, 2013]. Such techniques
521 might be called “fingerprinting” localization techniques as all the peculiar characteristics of the
522 multipath at a given position (the multipath “fingerprint”) are used to localize the mobile terminal.
523 Cooperative localisation techniques have also been proposed as a way to improve accuracy [*Win et*
524 *al.*, 2011; *Wymeersch et al.*, 2009; *Shen et al.*, 2010].

525 Recently, the use of RT together with indoor maps to empower localization techniques based on
526 the exploitation of Virtual Anchor Nodes (VAN) has been proposed [*Meissner et al.*, 2013]. The
527 method is based on the use of images of the access point or of Anchor Nodes with respect to the
528 room's main walls as virtual sources of waves: position-related information requires the estimation
529 of the energy ratio of deterministic reflected multipath component (MPC) and diffuse multipath
530 component (DMC). The DMC is introduced in order to model the non-specular part of the channel.

531 Thus, Ray Tracing is used to derive the position of the VAN's on the base of digital maps and the
532 corresponding estimated field. Although the accuracy of the method needs to be assisted through
533 proper calibration, a calibrated RT tool would enable replacement of time-consuming measurement
534 campaigns by offline RT simulations before installing the indoor localization system.

535 **5. Conclusions**

536 A survey of RT propagation modeling for future small-cell mm-wave systems is given in the
537 paper, with particular emphasis on open issues and on the application potential.

538 The 3D RT model developed at the University of Bologna (3Dscat) is taken as a reference,
539 showing how problems such as the efficient diffuse scattering computation have been addressed and
540 solved in the model.

541 Then the multi-dimensional prediction potential of RT is assessed, including MIMO
542 performance parameters estimation, and explaining how RT should be used and parametrized to
543 achieve optimum results. Results show that a good multidimensional prediction accuracy can be
544 achieved, but accurate material parameters should be used. Proper modeling of the diffuse
545 scattering interaction due to irregularities in walls or to the presence of environment cluttering
546 seems to be crucial to get good results especially for outdoor applications.

547 Last, promising RT applications for future wireless systems are illustrated. In particular the
548 possibility of using RT *inside* the system for real-time channel prediction to assist beamforming
549 techniques in gigabit-wireless access systems is shown, and preliminary simulation results confirm
550 the validity of the approach.

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809 **Figure 1.** Measured vs simulated Received Power (a) and Condition Number (b) along a corridor in
 810 an indoor office scenario.

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812 **Figure 2** – Comparison between measured and simulated MIMO Capacity in a Manhattan-like outdoor
 813 scenario ($S=0.4$ has been here considered)

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815 **Figure 3** – Measured power-angle spectrum for route 4 (street crossing scenario in Helsinki downtown)

816 **Figure 4** – Predicted power-angle spectrum for route 4 with rough angular discretization
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818 **Figure 5** – Predicted power-angle spectrum for route 4 with improved angular discretization (analytical
819 formula has been used to account for diffuse scattering contributions)
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821 **Figure 6** – Representation of the Helsinki scenario with Tx positions and Rx measurement routes.
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824 **Fig. 7.** Measured vs. simulated DS values for the exhibition hall of the Messe Berlin.

825
826 **Figure 8.** Detail of the reinforcing metal mesh in the floor of the hall.

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828 **Figure 9** – PAD in 'section (2)' of route GH, with respect to the radial direction.

Figure 10 – Indoor simulation environment with AP (Tx), mobile user, interferer, walls and furniture. User's and interferer's beams are depicted in blue and red, respectively.

Figure 11 – Mean SINR with 2 users per cell, with different beamforming solutions.

835 **Table 1.** Measured and predicted values for the correlation coefficients and the Rice factor

Meas. Sim.	Mean	Std dev.	Min	Max
$ \rho_{11-21} $	0.24	0.11	0.07	0.42
	0.19	0.11	0.05	0.41
$ \rho_{12-22} $	0.29	0.15	0.1	0.52
	0.21	0.15	0.06	0.61
$ \rho_{11-12} $	0.31	0.10	0.1	0.42
	0.25	0.11	0.1	0.49
$ \rho_{21-22} $	0.24	0.2	0.03	0.61
	0.26	0.13	0.06	0.46
$ \rho_{11-22} $	0.22	0.13	0.04	0.5
	0.19	0.14	0.08	0.44
$ \rho_{12-21} $	0.29	0.14	0.07	0.5
	0.14	0.07	0.04	0.26
K_{dB}	3.14	2.43	0.02	6.41
	2.47	1.85	0.08	6.75

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