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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

29 computation time and for the unavailability of detailed and reliable environment description  
30 databases. For these reasons a relevant effort within the scientific community addressed topics such  
31 as CPU time reduction through the decomposition of the 3D problem into one or more 2D problems  
32 [*Liang and Bertoni, 1998; Rossi and Gabillet, 2002*] or using techniques to increase the efficiency  
33 of the algorithm or to simplify the input database [*Hoppe et al., 2003; Degli-Esposti et al., 2009a*].  
34 Things are probably going to change. With the advent of modern wideband, high speed mobile  
35 radio systems adopting MIMO, beamforming and other advanced transmission techniques,  
36 performance no longer depends only on signal-to-noise ratio (SNR) but also on the multi-dispersive  
37 characteristics of the radio channel. Thanks to their intrinsic capability to simulate multipath  
38 propagation, RT models seem therefore a good solution to provide an accurate, site-specific field  
39 prediction and a multidimensional characterization of radio propagation channel in the time, space  
40 and polarization domains [*Liang and Bertoni, 1998; Athanasiadou et al., 2000; Kloch et al., 2001;*  
41 *Degli-Esposti et al., 2001, 2004; Rossi and Gabillet, 2002; Hoppe et al., 2003; Tila et al., 2003; Ng*  
42 *et al., 2007, Fuschini et al., 2008, Corre et al., 2009*]. In order to fully achieve this potential,  
43 extensions to describe diffuse scattering phenomena have been recently developed to account for  
44 the signal scattered in other than the specular direction due to surface and volume details and  
45 irregularities of building walls [*Degli-Esposti, 2001; Didascalou et al., 2003; Degli-Esposti et al.*  
46 *2007a; Kwakernaat and Herben, 2010; Mani and Oestges, 2011; Mani et al., 2012; Lu et al.,*  
47 *2014a, Cocheril et al. 2006*].

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

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

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

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

## 74 75 **2. State of the art of RT techniques for radio propagation modeling**

76 This section illustrates the main issues related to ray tracing deterministic propagation modeling  
77 with reference to the full three-dimensional (3D) RT tool developed at the University of Bologna  
78 named 3DScat; beside "standard" interactions such as reflection/diffraction/transmission adopting  
79 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  $\theta$  and  $\varphi$  a test ray scanning from  
129  $\theta=0^\circ$  to  $\theta=180^\circ$  and from  $\varphi=0^\circ$  to  $\varphi=360^\circ$  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



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

164 The prediction performance of RT models obviously depends on several factors, including the  
165 electromagnetic parameters of the walls/objects, (as highlighted in section 3.3) and the parameters  
166 of the DS model. With regard to the latter, an extensive validation and parameterization has been  
167 done in the recent years by means of experimental investigations in several types of environment.  
168 The main parameters of the ER model are the scattering coefficient  $S$  (with  $0 < S < 1$ ), directly related  
169 to the overall amount of power scattered at the expense of specular reflection, and the scattering  
170 radiation pattern, describing how the scattered power is distributed in space. The ER model is  
171 *physically sound*, because the scattered power due to wall irregularities is subtracted from specular  
172 reflection, introducing a proper reflection reduction factor  $R = \sqrt{1 - S^2}$  (with  $0 < R < 1$ ), thus  
173 preserving overall power balance [Degli-Esposti et al., 2007a]. According to [Degli-Esposti et al.,  
174 2007a, Mani et al., 2011]  $S$  can vary between 0.2 and 0.4 in rural environments, while higher  
175 values, up to 0.6, can be reached in scenarios with complex building structures [Vitucci et al.,  
176 2012]. As for the scattering pattern, recent studies have shown that satisfactory results can be  
177 obtained by assuming a single-lobe pattern centred on the direction of the specular reflection; in  
178 particular, the power density of DS is proportional to:

179 
$$S(\psi_R) = \left( \frac{1 + \cos \psi_R}{2} \right)^\alpha \quad (1)$$

180 where  $\psi_R$  is the angle between the specular reflection direction and the scattering direction, and  $\alpha$   
181 is a coefficient that sets the width of the scattering lobe. Typical values of  $\alpha$  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  $K_{\text{xpol}}$ , 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.  $K_{\text{xpol}}$  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  $K_{\text{xpol}}$  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  $7\lambda$   
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 ( $\rho_{11-12}$ ,  $\rho_{21-$   
281  $22$ ), at Rx side ( $\rho_{11-21}$ ,  $\rho_{12-22}$ ), and between cross-channels (diagonal correlations,  $\rho_{11-22}$ ,  $\rho_{12-21}$ ), being

282  $\mathbf{H} = \{h_{ij}\}_{\substack{i=1,2 \\ j=1,2}}$  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].



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

### 362 3.3 Sensitivity of RT prediction to environment modelling

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

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

379 The impact of such inaccuracies in the digital maps should be of course evaluated case by case;  
380 according to the study carried out in [Rizk et al., 2000] related to ray-tracing based prediction in  
381 urban microcells, errors in the walls position within  $\pm 2$  m in the 95% of cases correspond to an  
382 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  $\pm 1$  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  $\epsilon_R$  and the conductivity  $\sigma$ ) 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 ( $\sigma_\xi$ ) 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  $\sigma_\xi$  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  $2 \times 8$  or  $12 \times 12$  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  $2 \times 8$  array, and the increase is even greater for the  $12 \times 12$  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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## 560 **References**

561 3GPP TS 36.305, Stage 2 functional specification of User Equipment (UE) positioning in E-  
562 UTRAN (Rel. 9);

563 Athanasiadou, G.E., A.R. Nix, and J. P. McGeehan (2000), A Microcellular Ray-tracing  
564 Propagation Model and Evaluation of Its Narrow-Band and Wide-Band Predictions, *IEEE*  
565 *Journal on Selected Areas in Communications*, 18(3), 322-335, doi: 10.1109/49.840192;

566 Balanis, C.A. (1989), *Advanced Engineering Electromagnetics*, Wiley & Sons;

567 Barbiroli, M., V. Degli-Esposti, G. Falciassecca, F. Fuschini, L. Tian and E. M. Vitucci (2014),  
568 Study of the Multipath Distribution in Urban Environment for 5G Mobile Radio, paper presented  
569 at XX Riunione Nazionale di Elettromagnetismo (RINEM), Padova, Italy;

570 Bertoni, H.L. (2000), *Radio Propagation for Modern Wireless Systems*, Prentice Hall;

571 Catrein, D., M. Reyer, and T. Rick (2007), Accelerating Radio Wave Propagation Predictions by  
572 Implementation on Graphics Hardware, in *Proceedings of the 65<sup>th</sup> IEEE Vehicular Technology*  
573 *Conference (VTC Spring 2007)*, 510-514, doi: 10.1109/VETECS.2007.116;

574 Chizhik, D., J. Ling, P.W. Wolniansky, R.A. Valenzuela, N. Costa, and K. Huber (2003), Multiple-  
575 Input–Multiple-Output Measurements and Modeling in Manhattan, *IEEE Journal Selected Areas*  
576 *Comm.*, 21(3), 321-331, doi: [10.1109/JSAC.2003.809457](https://doi.org/10.1109/JSAC.2003.809457);

577 Cocheril, Y., R. Vauzelle, L. Aveneau, (2006), 3D Channel Simulations Including Scattering from  
578 Non-Gaussian Rough Surfaces, in *Proceedings of the 64<sup>th</sup> IEEE Vehicular Technology*  
579 *Conference (VTC Fall 2006)*, 1-5, doi: 10.1109/VTCF.2006.32;

580 Coldrey, M., H. Koorapaty, J. E. Berg, Z. Ghebretensaé, J. Hansryd, A. Derneryd, and S. Falahati  
581 (2012), Small-Cell Wireless Backhauling: A Non-Line-of-Sight Approach for Point-to-Point  
582 Microwave Links, *IEEE Vehicular Tech. Conference (VTC Fall)*, 1-5, doi:  
583 10.1109/VTCFall.2012.6399286;

584 Corre, Y., and Y. Lostanlen (2009), Three-Dimensional Urban EM Wave Propagation Model for  
585 Radio Network Planning and Optimization Over Large Areas, *IEEE Trans. on Vehicular Tech.*,  
586 58(7), 3112-3123, doi: 10.1109/TVT.2009.2016973;

587 Clerckx, B., and C. Oestges (2013), *MIMO Wireless Networks: Channels, Techniques and*  
588 *Standards for Multi-Antenna, Multi-User and Multi-Cell Systems*, Academic Press, Elsevier;

589 Cuinas, I., J.P. Pugliese, A. Hammoudeh, and M.G. Sanchez (2001), Frequency dependence of  
590 dielectric constant of construction materials in microwave and millimeter-wave bands,  
591 *Microwave and Optical Technology Letters*, 30(2), 123-124, doi: 10.1002/mop.1238;

- 592 Dardari, D., A. Conti, U. Ferner, A. Giorgetti, and M. Z. Win (2009), Ranging with ultrawide  
593 bandwidth signals in multipath environments, *Proceedings of the IEEE*, 97(2), 404-426, doi:  
594 10.1109/JPROC.2008.2008846
- 595 Degli-Esposti, V., G. Lombardi, C. Passerini, and G. Riva (2001), Wide-band measurement and  
596 ray-tracing simulation of the 1900-MHz indoor propagation channel: Comparison criteria and  
597 results, *IEEE Trans. Antennas Propagat.*, 49(7), 1101–1110, doi: 10.1109/8.933490;
- 598 Degli-Esposti, V., D. Guiducci, A. de’Marsi, P. Azzi, and F. Fuschini (2004), An advanced field  
599 prediction model including diffuse scattering, *IEEE Trans. Antennas Propagat.*, 52(7), 1717–  
600 1728, doi: 10.1109/TAP.2004.831299;
- 601 Degli-Esposti, V., F. Fuschini, E.M. Vitucci, and G. Falciasecca (2007a), Measurement and  
602 Modelling of Scattering From Buildings, *IEEE Trans. Antennas Propagat.*, 55(1), 143-153, doi:  
603 10.1109/TAP.2006.888422;
- 604 Degli-Esposti, V., V.-M. Kolmonen, E. M. Vitucci, F. Fuschini, and P. Vainikainen (2007b),  
605 Analysis and ray tracing modelling of co- and cross-polarization radio propagation in urban  
606 environment, 2<sup>nd</sup> European Conference on Antennas and Propagation (EuCAP 2007), 1-4;
- 607 Degli-Esposti, V., F. Fuschini, E. M. Vitucci, and G. Falciasecca (2009a), Speed-up techniques for  
608 ray tracing field prediction models, *IEEE Trans. Antennas Propagat.*, 57(5), 1469–1480, doi:  
609 10.1109/TAP.2009.2016696;
- 610 Degli-Esposti, V., F. Fuschini, and E. M. Vitucci (2009b), A fast model for distributed scattering  
611 from buildings, 3<sup>rd</sup> European Conference on Antennas and Propagation (EuCAP 2009), 1932-  
612 1936;
- 613 Degli-Esposti, V., V.-M. Kolmonen, E. M. Vitucci, and P. Vainikainen (2011), Analysis and  
614 modeling on co- and cross-polarized urban radio propagation for dual-polarized MIMO wireless  
615 systems, *IEEE Trans. Antennas Propagat.*, 59(11), 4247–4256, doi: 10.1109/TAP.2011.2164226;
- 616 Didascalou, D., M. Döttling, N. Geng, and W. Wiesbeck (2003), An approach to include stochastic  
617 rough surface scattering into deterministic ray optical wave propagation modeling, *IEEE Trans.*  
618 *Antennas Propag.*, 51(7), 1508–1515, doi: 10.1109/TAP.2003.813600;
- 619 Dupleich, D., F. Fuschini, R. Mueller, E. Vitucci, C. Schneider, V. Degli Esposti and R. Thomä  
620 (2014), Directional characterization of the 60 GHz indoor-office channel, paper presented at 31th  
621 URSI General Assembly and Scientific Symposium, Beijing, China;
- 622 Felsen, L.B., and N. Marcuvitz (1973), *Radiation and Scattering of Waves*, Prentice Hall; IEEE  
623 Press;
- 624 Fessler, J.A. and A.O. Hero (1994), Space-alternating generalized expectation maximization  
625 algorithm, *IEEE Trans. Signal Process.*, 42(10), 2664–2677, doi: [10.1109/78.324732](https://doi.org/10.1109/78.324732).
- 626 Fugen, T., J. Maurer, T. Kayser, and W. Wiesbeck (2006), Capability of 3-D Ray Tracing for  
627 Defining Parameter Sets for the Specification of Future Mobile Communications Systems, *IEEE*  
628 *Trans. Antennas Propagat.*, 54(11), 3125-3137, doi: 10.1109/TAP.2006.883988;
- 629 Fuschini, F., H. El-Sallabi, V. Degli-Esposti, L. Vuokko, D. Guiducci, and P. Vainikainen (2008),  
630 Analysis of multipath propagation in urban environment through multidimensional  
631 measurements and advanced ray tracing simulation, *IEEE Trans. Antennas Propagat.*, 56(3), 848  
632 – 857, doi: 10.1109/TAP.2008.916893;

- 633 Ghaddar, M., L. Talbi, G.Y. Delisle, and J. LeBel (2013), Deflecting-Obstacle Effects on Signal  
634 Propagation in the 60 GHz Band, *IEEE Trans. Antennas and Propagation*, 61(1), 403-414, doi:  
635 10.1109/TAP.2012.2216852;
- 636 Giorgetti, A., and M. Chiani (2013), Time-of-arrival estimation based on information theoretic  
637 criteria, *IEEE Transactions on Signal Processing*, 62(8), 1869-1879, doi:  
638 10.1109/TSP.2013.2239643;
- 639 Glassner, A.S. (1984), Space subdivision for fast ray tracing, *IEEE Computer Graphics*  
640 *Applications*, 4(10) 15-24, doi: 10.1109/MCG.1984.6429331;
- 641 Gustafson, C., K. Haneda, S. Wyne, and F. Tufvesson (2014), On mm-Wave Multipath Clustering  
642 and Channel Modeling, *IEEE Trans. Antennas Propagat.*, 62(3), 1445-1455, doi:  
643 10.1109/TAP.2013.2295836;
- 644 Hansen, C.J. (2011), WiGiG: Multi-gigabit wireless communications in the 60 GHz band, *IEEE*  
645 *Wireless Communications*, 18(6), 6-7, doi: 10.1109/MWC.2011.6108325;
- 646 Hata, M. (1980), Empirical Formula for Propagation Loss in Land Mobile Radio Services, *IEEE*  
647 *Trans. on Vehicular Tech.*, 29(3), 317-325, doi: 10.1109/T-VT.1980.23859;
- 648 Hatami, H., B. Alavi, K. Pahlavan, and M. Kanaan (2006), A comparative performance evaluation  
649 of indoor geolocation technologies, *Interdisciplinary Information Sciences*, 12(2), 133-146;
- 650 Hoppe, R., G. Woelfle, and P. Wertz (2003), Advanced ray-optical wave propagation modelling for  
651 urban and indoor scenarios, *European Transactions on Telecommunications (ETT)*, 14(1),61-69;
- 652 Jacob, M., S. Priebe, T. Kurner, M. Peter, M. Wisotzki, R. Felbecker, and W. Keusgen (2013),  
653 Extension and validation of the IEEE 802.11ad 60 GHz human blockage model, 7th Eur. Conf.  
654 on Antennas and Propagation (EuCAP 2013), 2806-2810;
- 655 Kaplan, M.R (1985), The uses of spatial coherence in ray tracing, *SIGGRAPH '85 Course notes no*  
656 *11*;
- 657 Kazemi, M.J., A. Abdipur, and A. Mohammadi (2012), Indoor propagation MIMO channel  
658 modeling in 60 GHz using SBR based 3D ray tracing technique, 2<sup>nd</sup> Conference on Millimeter-  
659 Wave and Terahertz Technologies (MMWaTT), 25-28, doi: 10.1109/MMWaTT.2012.6532159;
- 660 Kloch, C., G. Liang, J. B. Andersen, G. F. Pedersen, and H. L. Bertoni (2001), Comparison of  
661 Measured and Predicted Time Dispersion and Direction of Arrival for Multipath in a Small Cell  
662 Environment, *IEEE Trans. Antennas Propagat.*, 49(9), 1254-1263, doi: 10.1109/8.947016;
- 663 Kouyoumjian, R.G., and P.H. Pathak (1974), A uniform GTD for an edge in a perfectly conducting  
664 surface, *Proc. IEEE*, 62(11), 1448-1461;
- 665 Kuang, Y., K. Åström, and F. Tufvesson (2013), Single antenna anchor-free UWB positioning  
666 based on multipath propagation, in *Proc. IEEE International Conference on Communications*  
667 *(ICC)*, 5814-5818, doi: 10.1109/ICC.2013.6655524;
- 668 Kwakkernaat, M.R., and M. H. Herben (2010), Angular dispersion of radio waves due to rough  
669 surface scattering in mobile channels, 4<sup>th</sup> European Conference on Antennas and Propagation  
670 (EuCAP 2010), 1-5;
- 671 Laaraiedh, M., B. Uguen, J. Stephan, Y. Corre, Y. Lostanlen, M. Raspopoulos, and S. Stavrou  
672 (2012), Ray Tracing-Based Radio Propagation Modeling for Indoor Localization Purposes, *IEEE*

673 17<sup>th</sup> Int. Workshop on Computer Aided Modeling and Design of Communication Links and  
674 Networks, 276-280, doi: 10.1109/CAMAD.2012.6335350;

675 Lai, Z., N. Bessis, G. de la Roche, P. Kuonen, J. Zhang, and G. Clapworthy (2009), A new  
676 approach to solve angular dispersion of discrete ray launching for urban scenarios,  
677 Loughborough Antennas & Propagation Conference (LAPC 2009), 133-136, doi:  
678 10.1109/LAPC.2009.5352420;

679 Larew, S.G., T.A. Thomas, M. Cudak, and A. Ghosh (2013), Air Interface and Ray Tracing Study  
680 for 5G Millimeter Wave Communications, IEEE Globecom Workshops, 117-122, doi:  
681 10.1109/GLOCOMW.2013.6824972;

682 Lee, B.S., A. R. Nix, and J. P. McGeehan (2001), A spatiotemporal ray launching propagation  
683 model for UMTS pico and microcellular environments, IEEE VTS 53rd Vehicular Technology  
684 Conference (VTC 2001 Spring), 1, 367-371;

685 Liang, G., and H. L. Bertoni (1998), A new approach to 3-D ray tracing for propagation prediction  
686 in cities, IEEE Trans. Antennas Propagat., 46(6), 853–863, doi: 10.1109/8.686774;

687 Liu, H., H. Darabi, P. Banerjee, and J. Liu (2007), Survey of wireless indoor positioning techniques  
688 and systems, IEEE Transactions on Man, Systems, and Cybernetics – Part C: Applications and  
689 Reviews, 37(6), 1067-1080, doi: 10.1109/TSMCC.2007.905750;

690 Lu, J.S., H. L. Bertoni, and V. Degli Esposti (2014a), Scale Model Investigation of Mechanisms for  
691 Scattering from Office Buildings at 2 GHz, IEEE Trans. Antennas Propagat., 62(12), 6435-6442,  
692 doi: 10.1109/TAP.2014.2362115;

693 Lu, J., D. Steinbach, P. Cabrol, P. Pietraski, and R.V. Pragada (2014b), Propagation  
694 Characterization of an Office Building in the 60 GHz Band, paper presented at 8<sup>th</sup> European  
695 Conference on Antennas and Propagation (EuCAP 2014), The Hague, The Netherlands;

696 Mani, F., and C. Oestges (2011), Ray-tracing evaluation of diffuse scattering in an outdoor scenario,  
697 5<sup>th</sup> European Conference on Antennas and Propagation (EuCAP 2011), 3439-3443;

698 Mani, F., F. Quitin, and C. Oestges (2011), Accuracy of depolarization and delay spread predictions  
699 using advanced ray-based modeling in indoor scenarios, EURASIP Journal on wireless  
700 communications and networking, 11(1), doi: 10.1186/1687-1499-2011-11;

701 Mani, F., F. Quitin, and C. Oestges (2012), Directional spreads of dense multipath components in  
702 indoor environments: Experimental validation of a ray-tracing approach, IEEE Trans. Antennas  
703 Propagat., 60(7), 3389–3396, doi: 10.1109/TAP.2012.2196942;

704 Mani, F., E. M. Vitucci, F. Quitin, V. Degli-Esposti, and C. Oestges (2014), Parameterization of a  
705 Polarimetric Diffuse Scattering Model in Indoor Environments, IEEE Trans. Antennas Propagat.,  
706 62(8), doi: 10.1109/TAP.2014.2322901;

707 Mckown, J.W., and R.L. Hamilton (1991), Ray Tracing as a Design Tool for Radio Networks, IEEE  
708 Network Magazine, 5, 27-30, doi: 10.1109/65.103807;

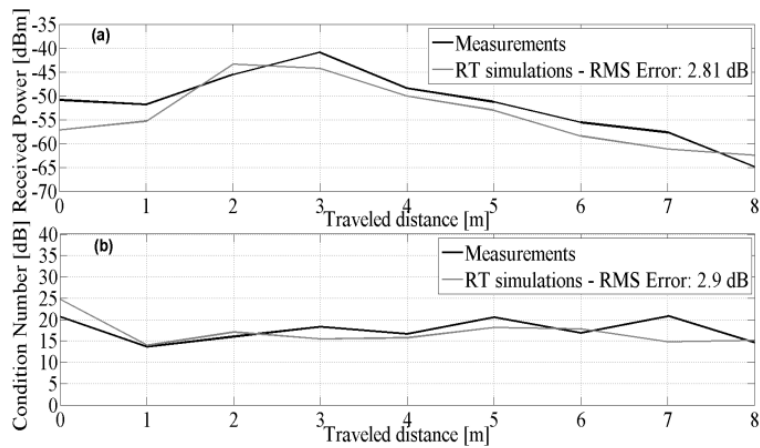
709 Meissner, P., M. Gan, F. Mani, E. Leitinger, M. Frohle, C. Oestges, T. Zemen, and K. Witrisal  
710 (2013), On the use of ray tracing for performance prediction of UWB indoor localization  
711 systems, IEEE International Conference on Communications Workshops (ICC), 68-73, doi:  
712 10.1109/ICCW.2013.6649203;

- 713 Ng, K.H., E.K. Tameh, A. Doufexi, M. Hunukumbure, and A.R. Nix (2007), Efficient Multielement  
714 Ray Tracing With Site-Specific Comparisons Using Measured MIMO Channel Data, *IEEE*  
715 *Trans. on Vehicular Tech.*, Volume: 56(3), 1019 – 1032, doi: 10.1109/TVT.2007.895606;
- 716 NVIDIA CORPORATION, CUDA Compute Unified Device Architecture Programming Guide,  
717 [Online]. Available: [http://developer.nvidia.com/object/cuda\\_get.html](http://developer.nvidia.com/object/cuda_get.html);
- 718 Ouattara, Y.B., E. Richalot, O. Picon, G. Kubicke, C. Bourlier, J. Wiart (2011), Radiowaves  
719 scattering from irregular building facades through MoM analysis, 5th European Conf. Antennas  
720 and Propagation (EuCAP 2011), 3424-3428;
- 721 Pahlavan, K., X. Li, and J.-P. Mäkelä (2002), Indoor geolocation science and technology, *IEEE*  
722 *Communications Magazine*, 40(2), 112-118, doi: 10.1109/35.983917;
- 723 Pahlavan, K., F.O. Akgul, M. Heidari, and A. Hatami (2006), Indoor geolocation in the absence of  
724 direct path, *IEEE Wireless Communications*, 13(6), 50-58, doi: 10.1109/MWC.2006.275198;
- 725 Papakonstantinou, K., and D. Slock (2009), Hybrid TOA/AOD/Doppler-shift localisation algorithm  
726 for NLOS Environments, in *Proc. IEEE 20th International Symposium on Personal, Indoor and*  
727 *Mobile Radio Communications (PIMRC)*, 1948-1952, doi: 10.1109/PIMRC.2009.5450008;
- 728 Parsons, J. D. (2000), *The Mobile Radio Propagation Channel*, Wiley & Sons;
- 729 Peter, W., W. Keusgen, and R. Felbecker (2007), Measurement and ray-tracing simulation of the 60  
730 GHz indoor broadband channel: model accuracy and parameterization, 2nd European Conf.  
731 Antennas and Propagation (EuCAP 2007), 1-8;
- 732 Priebe, S., M. Kannicht, M. Jacob, and T. Kürner (2013), Ultra Broadband Indoor Channel  
733 Measurements and Calibrated Ray Tracing Propagation Modeling at THz Frequencies, *Journal*  
734 *of Communications and Networks*, 15(6), 547-558, doi: 10.1109/JCN.2013.000103;
- 735 Rappaport, T.S., S. Sun, R. Myzus, H. Zhao, Y. Azar, K. Wang, G.N. Wong, J.K. Schulz, M.  
736 Samimi, and F. Gutierrez (2013), Millimeter Wave Mobile Communication for 5G Cellular: It  
737 Will Work!, *IEEE Access*, 1, 335-349, doi: 10.1109/ACCESS.2013.2260813;
- 738 Rasekh, M.E., A.A. Shishegar, and F. Farzaneh (2009), A study of the effect of diffraction and  
739 rough surface scatter modeling on ray tracing results in an urban environment at 60 GHz, 1<sup>st</sup>  
740 Conference on Millimeter-Wave and Terahertz Technologies (MMWaTT) , 27-31, doi:  
741 10.1109/MMWATT.2009.5450459;
- 742 Rashid-Farrokhi, F., A. Lozano, G. Foschini, and R.A.Valenzuela (2000), Spectral efficiency of  
743 wireless systems with multiple transmit and receive antennas, *IEEE Int. Symp. on Personal,*  
744 *Indoor and Mobile Radio Communications (PIMRC)*, 1, 373–377, doi:  
745 10.1109/PIMRC.2000.881451;
- 746 Reynaud, S., R. Vauzelle, A. Reineix, C. Guiffaut, (2007), Hybrid FDTD/UTD radio wave  
747 propagation modeling: application indoor channels simulations, *Microwave and Optical*  
748 *Technology Letters*, 49(6), 1312-1320, doi: 10.1002/mop.22431;
- 749 Rich, T., and T. Kuhlen (2010), Accelerating Radio Wave Propagation Algorithms by  
750 Implementation on Graphics Hardware, in *Wave Propagation in Materials for Modern*  
751 *Applications* edited by by A. Petrin, pp. 103-124, InTech Publishing;
- 752 Rizk, K., J.F. Wagen, and F. Gardiol (2000), “Influence of Database Accuracy on Two-  
753 Dimensional Ray-Tracing-Based Predictions in Urban Microcells”, *IEEE Trans. Vehicular*  
754 *Tech.*, 49(2), 631 – 642, doi: 10.1109/25.832995;

- 755 Roh, W., J.-Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar (2014),  
756 Millimeter-Wave Beamforming as an Enabling Technology for 5G Cellular Communications:  
757 Theoretical Feasibility and Prototype Results, *IEEE Comm. Magazine*, 52(2), 106-113, doi:  
758 10.1109/MCOM.2014.6736750;
- 759 Rose, D. M., and T. Kurner (2014), An Analytical 3D Ray-Launching Method Using Arbitrary  
760 Polygonal Shapes for Wireless Propagation Prediction, 80th IEEE Vehicular Technology  
761 Conference (VTC Fall), 14-17, doi: 10.1109/VTCFall.2014.6965865;
- 762 Rossi, J.P., J.C. Bic, A.J. Levy, Y. Gahillet, and M. Rosen (1991), A Ray Launching Method for  
763 Radio-mobile Propagation in Urban Area, *IEEE International Symposium on Antennas and*  
764 *Propagation Digest*, 3, 1540-1543, doi: 10.1109/APS.1991.175146;
- 765 Rossi, J.P., and Y. Gahillet (2002), A mixed ray launching/tracing method for full 3-D UHF  
766 propagation modeling and comparison with wide-band measurements, *IEEE Trans. Antennas*  
767 *and Propagation*, 50(4), 517-523, doi: 10.1109/TAP.2002.1003388;
- 768 Sczyslo, S., S. Dortmund and I. Rolfes (2012), Determination of the Delay Spread of an Indoor  
769 Channel Measurement Campaign in the UHF Band, *Proc. of Antennas and Propagation Society*  
770 *International Symposium (AP-S URSI)*, 1-2, doi: 10.1109/APS.2012.6348846;
- 771 Seidel, S.Y., and T.S. Rappaport (1992), A ray tracing technique to predict path loss and delay  
772 spread inside buildings, *IEEE Global Telecommunication Conference*, 2, 649-652, doi:  
773 10.1109/GLOCOM.1992.276436;
- 774 Shen, Y., H. Wymeersch, and M. Z. Win (2010), Fundamental limits of wideband localization - Part  
775 II: Cooperative networks, *IEEE Transactions on Information Theory*, 56(10), 4981-5000, doi:  
776 10.1109/TIT.2010.2059720;
- 777 Shi, L., and T. Wigren (2009), AECID fingerprinting positioning performance, *IEEE Global*  
778 *Telecommunications Conference (Globecom 2009)*, 1-6, doi: 10.1109/GLOCOM.2009.5425928;
- 779 Tila, F., P.R. Shepherd, and S.R. Pennock (2003), Theoretical capacity evaluation of indoor micro-  
780 and macro-MIMO systems at 5 GHz using site specific ray tracing, *Electronics Letters*, 39(5),  
781 471-472, doi: 10.1049/el:20030310;
- 782 Vitucci, E.M., V. Degli-Esposti, and F. Fuschini (2006), MIMO channel characterization through  
783 ray tracing simulation, 1<sup>st</sup> European Conference on Antennas and Propagation (EuCAP2006), 1-  
784 6, doi: 10.1109/EUCAP.2006.4584732;
- 785 Vitucci, E.M., V.-M. Kolmonen, V. Degli-Esposti, and P. Vainikainen (2008), Analysis of Radio  
786 Propagation in Co- and Cross-Polarization in Urban environment, in *Proc. 10<sup>th</sup> International*  
787 *Symposium on Spread Spectrum Techniques and Applications (ISSSTA 2008)*, 277-281; doi:  
788 10.1109/ISSSTA.2008.56;
- 789 Vitucci, E.M, F. Mani, V. Degli-Esposti, and C. Oestges (2012), Polarimetric Properties of Diffuse  
790 Scattering from Building Walls: Experimental Parameterization of a Ray-Tracing Model, *IEEE*  
791 *Trans. Antennas Propagat.*, 60(6), 2961-2969, doi: 10.1109/TAP.2012.2194683;
- 792 Vitucci, E.M., L. Tarlazzi, F. Fuschini, P. Faccin, and V. Degli Esposti (2014), Interleaved MIMO  
793 DAS for Indoor Radio Coverage: Concept and Performance Assessment, *IEEE Trans. Antennas*  
794 *Propagat.*, 62(6), 3299-3309, doi: 10.1109/TAP.2014.2313136;

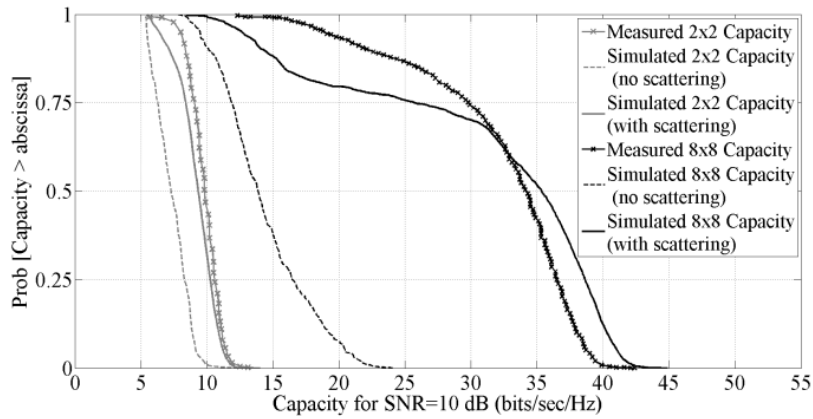
- 795 Win, M.Z., A. Conti, S. Mazuelas, S. Yuan, W.M. Gifford, D. Dardari, and M. Chiani, (2011),  
796 Network localization and navigation via cooperation, *IEEE Communications Magazine*, 49(5),  
797 56-62, doi: 10.1109/MCOM.2011.5762798;
- 798 Wymeersch, H., J. Lien, and M. Z. Win (2009), Cooperative localization in wireless networks,  
799 *Proceedings of the IEEE*, 97(2), 427–450, doi: 10.1109/JPROC.2008.2008853;
- 800 Yubo, T., H. Lin, and H. Bao (2010), GPU-Based Shooting and Bouncing Ray Method for Fast  
801 RCS Prediction, *IEEE Trans. Antennas Propagat.*, 58(2), 494-502, doi:  
802 10.1109/TAP.2009.2037694;
- 803 Zhu, M., A. Singh, and F. Tufvesson (2012), Measurement based ray launching for analysis of  
804 outdoor propagation, 6<sup>th</sup> European Conference on Antennas and Propagation (EuCAP 2012),  
805 3332-3336, doi: 10.1109/EuCAP.2012.6206329;
- 806

807



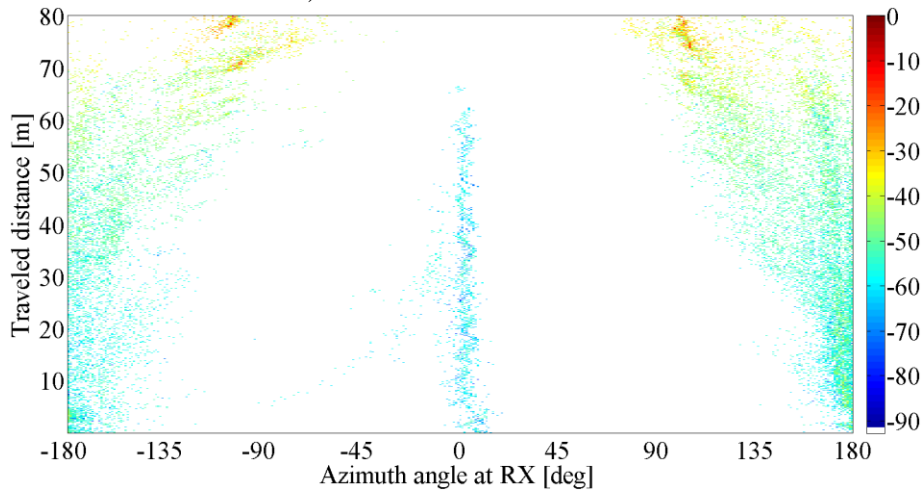
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809 **Figure 1.** Measured vs simulated Received Power (a) and Condition Number (b) along a corridor in  
810 an indoor office scenario.



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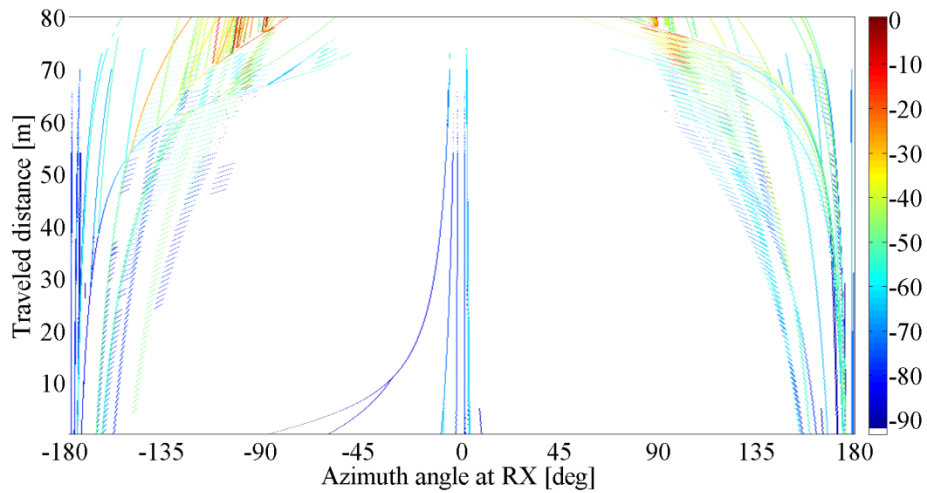
812 **Figure 2** – Comparison between measured and simulated MIMO Capacity in a Manhattan-like outdoor  
813 scenario ( $S=0.4$  has been here considered)



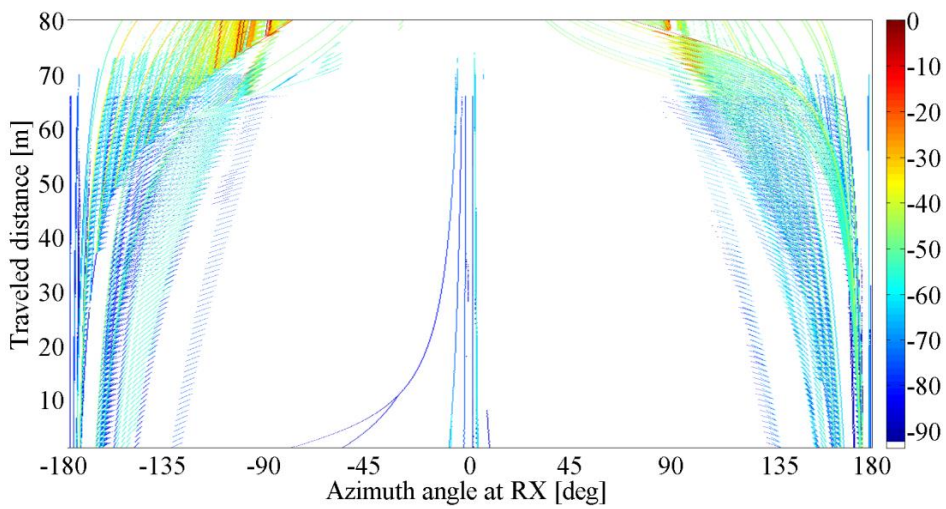
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815 **Figure 3** – Measured power-angle spectrum for route 4 (street crossing scenario in Helsinki downtown)

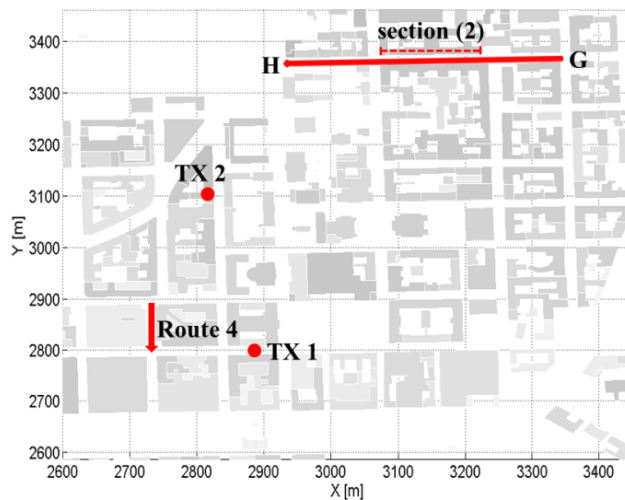




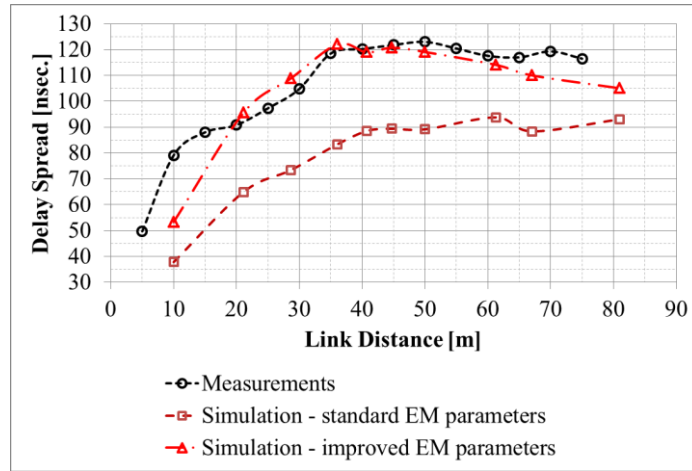
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817 **Figure 4** – Predicted power-angle spectrum for route 4 with rough angular discretization



818  
819 **Figure 5** – Predicted power-angle spectrum for route 4 with improved angular discretization (analytical  
820 formula has been used to account for diffuse scattering contributions)



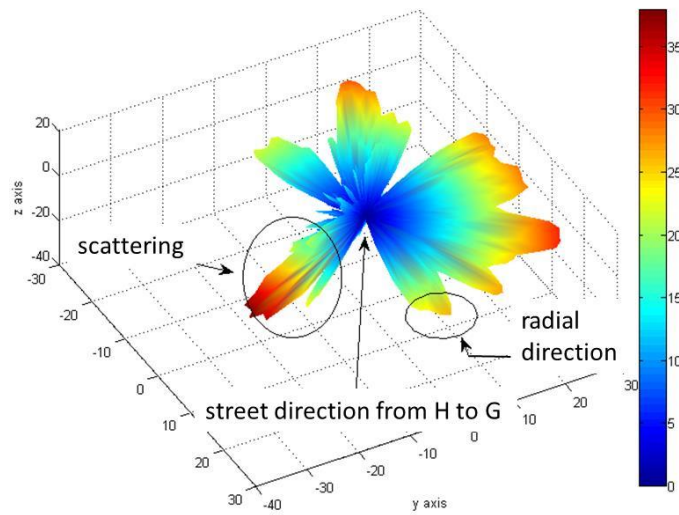
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822 **Figure 6** – Representation of the Helsinki scenario with Tx positions and Rx measurement routes.



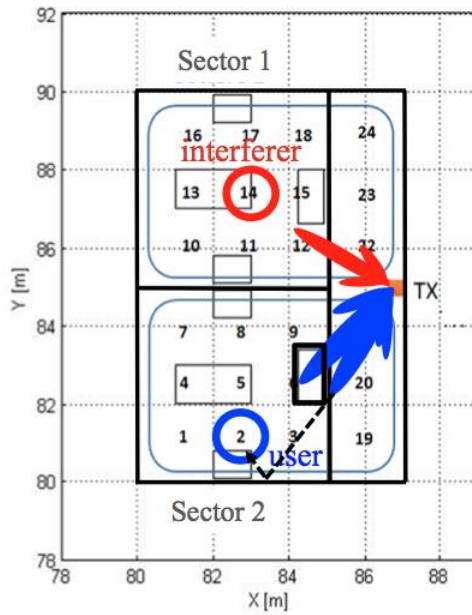
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824 **Fig. 7.** Measured vs. simulated DS values for the exhibition hall of the Messe Berlin.



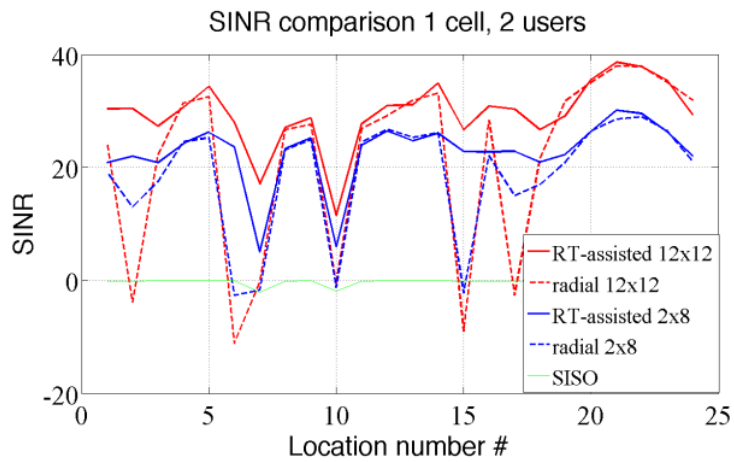
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826 **Figure 8.** Detail of the reinforcing metal mesh in the floor of the hall.



827  
828 **Figure 9** – PAD in 'section (2)' of route GH, with respect to the radial direction.



829  
 830 **Figure 10** – Indoor simulation environment with AP (Tx), mobile user, interferer, walls and furniture.  
 831 User's and interferer's beams are depicted in blue and red, respectively.



832  
 833 **Figure 11** – Mean SINR with 2 users per cell, with different beamforming solutions.  
 834

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

Meas.	Mean	Std dev.	Min	Max
$ \rho_{11-21} $	0.24	0.11	0.07	0.42
Sim.	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

836