Discussion of results and conclusions: Results are presented in Figs. 1 and 2. Both measurement and simulation results are reported and compared. Fig. 1 shows the mean measured path losses P_μ^j against the simulated values. In Fig. 2 the average spatial correlation function is shown for two different sets of Tx-Rx configurations: the first set collects paths for which the distance Tx-Rx is <10m while the second collects the remaining paths.

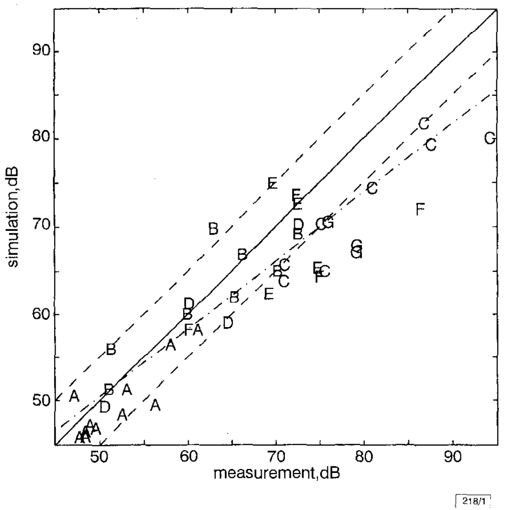

Fig. 1 *Measured against simulated narrowband path loss* (*f* = *1.89GHz*)

——— identity line
– – – – 10dB wide strip
–·–·–· regression line

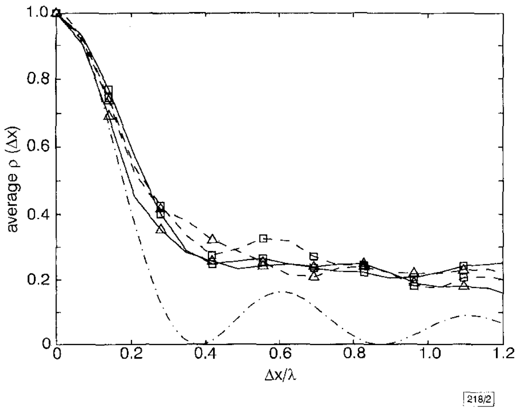

Fig. 2 *Spatial correlation coefficient for narrowband path loss* (*f* = *1.89GHz*)

——— simulation
– – – – measurement
□ locations below 10m
△ locations above 10m
–·–·–· theoretical, $\rho(\Delta x) = J_0(2\pi(\Delta x/\lambda))^2$

Fig. 1 shows that the RT simulation can accurately reproduce path loss, but a moderate, systematic underestimation of it emerges as link distance increases. Since the electromagnetic characteristics of a building, given as the input to the RT simulator, were tuned to closely reproduce single wall crossing attenuation, the cited error should not be attributed to an incorrect choice of electromagnetic parameters. Environmental clutter and the consequent power diffusion could be at least in part responsible for the systematic error [1]. Spatial correlation is well predicted by RT, however, no matter what the link distance is, as shown in Fig. 2, where Clarke's theoretic spatial correlation is also displayed as a reference. Moreover, good agreement with the results in [2, 3] is obtained. This fact is very interesting because it highlights the fact that RT correctly reproduces a very important statistical characteristic of multipath, even if the absolute value of path loss is subject to inaccuracies. Furthermore, also wideband parameters, such as time delay spread, show a similar spatial correlation behaviour [4, 5]. Such considerations show that ray tracing is able to correctly describe the propagation mechanisms in an indoor scenario, provided that a reasonably accurate characterisation of the environment is given, including the main pieces of furniture such as metal doors, shelves and cupboards.

Finally, it is worth noting that the quality of the reproduction of the spatial correlation confirms the validity of the ray optics approximation of the electromagnetic energy exchange in millimetre wave indoor propagation.

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References

1 LOMBARDI, G., DEGLI-ESPOSTI, V., PASSERINI, C., RIVA, G., and VALENTINUZZI, E.: 'Measurement and simulation of the DECT indoor propagation channel'. Proc. IEEE VTC '97, Phoenix, AZ, 5–7 May 1997, pp. 426–430

2 CORAZZA, G.E., DEGLI-ESPOSTI, V., FRULLONE, M., and RIVA, G.: 'A characterization of indoor space and frequency diversity by ray-tracing modelling', *IEEE J. Sel. Areas Commun.*, 1996, **SAC-14**, (3), pp. 411–419

3 HASHEMI, H.: 'Impulse response modeling of indoor radio propagation channels', *IEEE J. Sel. Areas Commun.*, 1993, **SAC-11**, (7), pp. 967–978

4 HASHEMI, H., and THOLL, D.: 'Statistical modeling and simulation of the RMS delay spread of indoor radio propagation channels', *IEEE Trans.*, 1994, **VT-43**, (1), pp. 110–120

5 LOMBARDI, G.: 'Measurement, simulation and analysis of indoor mobile channel'. PhD Thesis, Dip. di Elettrotecnica, Elettronica e Informatica, University of Trieste, Trieste, Italy, 1998 (in Italian)

Simulation model of urban polarisation cross-coupling

K. Siwiak and L.A. Ponce de Leon

A polarisation cross-coupling model is introduced for urban mobile radio channels. The model is based on reflected and diffracted ray paths in a homogenous urban region described in terms of average building heights and average street widths, and is suitable for evaluating mobile polarisation diversity reception.

Introduction: Signals in urban streets arrive by reflections from buildings, diffraction from rooftops, and diffraction with subsequent reflection. The physical mechanism characterised by those three ray paths in a homogenous urban region with average building heights and average street widths allows us to quantify the polarisation cross-coupling, which is important in the study of mobile polarisation diversity reception. The model correctly predicts the range of polarisation cross-coupling encountered in measurements, and the measurements are discussed.

Simulation of polarisation cross-coupling: The homogeneous urban environment can be generalised by an average street width *W* and an average building height *H* as seen in Fig. 1. The fields in the 'urban canyon' between buildings are due to diffraction from the rooftops and building edges along with reflections from buildings and from streets. We consider three ray paths here (see Fig. 1): a direct diffracted ray from the rooftop, and both diffracted and direct rays that are reflected from across the street, as was similarly considered in [1] to predict fields in urban streets.

Polarisation cross-coupling from a nominally vertical incident polarisation on the roof edge can be found by eqn. 1 using the edge diffraction coefficient G^+ from the GTD (geometric theory of diffraction) for scattering by a conducting wedge, see for example Siwiak [2], used here for vertical polarisation at near-grazing incidence on a horizontal roof edge.

$$G^+ = \frac{e^{-j\pi/[4\sin(2\pi/3)]}}{1.5\sqrt{2\pi k}} \frac{2}{\cos\left[\frac{2}{3}\pi\right] - \cos\left[\left(\theta + \frac{\pi}{2}\right)\frac{2}{3}\right]} \tag{1}$$

where *k* is the wave number and the angle θ is measured from the vertical *z*-axis. The resulting diffracted wave is polarised along the θ unit vector. The θ polarisation is then resolved into vertical (*z*-directed) and horizontal (ρ-directed) components. The tilt of θ with respect to the vertical and horizontal directions provides the mechanism for polarisation cross-coupling, and the subsequent localised TE and TM reflections tend to de-correlate the *z*- and ρ-components, rendering them suitable for diversity reception. The relative propagated diffracted power is proportional to the average over *x* (see Fig. 1) along the street width, of the diffraction coefficient $G^+(\theta)$ resolved into the vertical and horizontal polarisations, respectively:

$$Zpol(W/H) = \int_0^1 |G^+(\theta_1)|^2 \sin(\theta_1)^2 + R|G^+(\theta_2)|^2 \sin(\theta_2)^2 dx \tag{2}$$

$$\rho pol(W/H) = \int_0^1 |G^+(\theta_1)|^2 \cos(\theta_1)^2 + R|G^+(\theta_2)|^2 \cos(\theta_2)^2 dx \tag{3}$$

where the angles $\theta_1 = \pi - \mathrm{atan}[xW/(H-h)]$ and $\theta_2 = \pi - \mathrm{atan}[(2-x)W/(H-h)]$ are functions of *x*, *W* and *H* and are the diffracted path (ray 1 in Fig. 1), and the diffracted-reflected (ray path 2 in Fig. 1). The average power reflected from the building opposite the diffracting building is *R*, and *h* is the height of the field point above the street level. Here, $H \simeq H - h$. An additional component *R* in the denominator is reflected power in the vertical polarisation that is not due to diffraction (ray 3 in Fig. 1). A first-order equation for polarisation cross-coupling based on the three ray paths, and assuming similar antenna patterns for the two polarisations, is

$$X_{couple}(W/H) = 10\log\left[\frac{\rho pol(W/H)}{Zpol(W/H) + R}\right] \tag{4}$$

Both ρ*pol* and *Zpol* decrease with the square root of frequency because of the wave number term in eqn. 1; however, *R* is relatively independent of frequency.

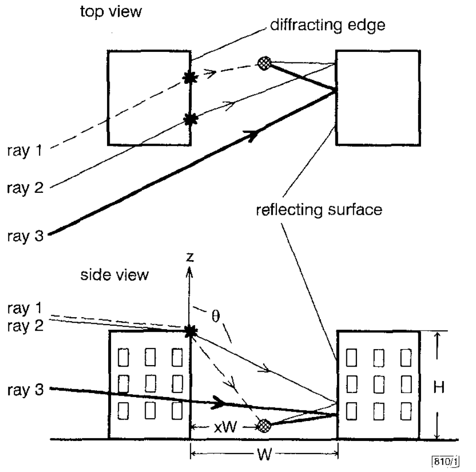

Fig. 1 *Nominal and cross-polarised signals averaged over street width*

(ray 1, ray 2) affected by diffraction
(ray 2, ray 3) affected by reflection
W: street width; *H*: building height

Fig. 2 shows the predicted polarisation cross-coupling at 800–900MHz for several values of reflection coefficient *R*. *W*/*H* ratios between 0.3 and ~6 represent typical heavy to light suburban ranges of urbanisation. Inspection of Fig. 2 reveals that X_{couple} can be closely approximated by

$$X_{couple} = -3.33\log\left[\left[\frac{W}{H}\right]^3 + 1.25\right] - 5.1 \tag{5}$$

in the 800–900MHz range for $R = 0.25$; hence, the diffraction polarisation coupling mechanism relates simply to a homogeneous urban environment generalised by the building width *W* to building height *H* ratio. Circles denote measurements in Tokyo by Taga [3], and the squares, each averaged over four trials, are measurements by the author (Ponce de Leon) in Boynton Beach, Florida.

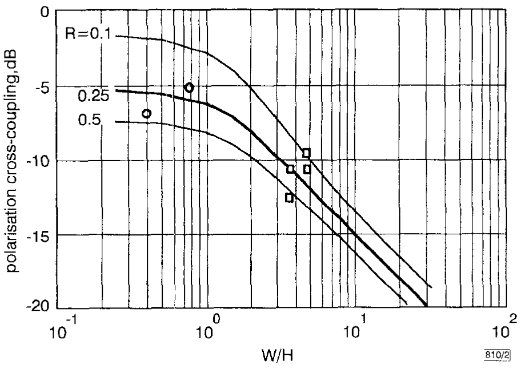

Fig. 2 *Cross-coupling of polarisation against street width to building height ratio and reflection level from buildings*

R: average power reflection coefficient
○ measurements reported by Taga [3]
☐ measurements reported in this Letter

Polarisation cross-coupling encountered in measurements: Cox *et al.* [4] reported measurements of cross-coupling from the transmitted vertical to received horizontal polarisations in and around commercial buildings and residential houses at between –3.9 and –8.6dB; however, they do not report the street or building geometry. The range agrees with office area measurements of between 0 and –6dB made by the author (Ponce de Leon). Polarisation cross-coupling measurements outside buildings in urban areas range between –4 and –9dB according to Lee and Yeh in [5], and –5.1 and –6.8dB according to Taga [3] on two urban routes (Ningyo-cho, *W*/*H* = 0.76 and Kabuto-cho, *W*/*H* = 0.4) in Tokyo.

Summary: A polarisation cross-coupling model, suitable for polarisation diversity reception analysis, is introduced for urban mobile radio channels. The model presents a mechanism for polarisation cross-coupling based on rays that arrive by reflections from buildings, diffraction from rooftops, and diffraction with subsequent reflection in a homogenous urban region describable by average building heights and average street widths. It correctly predicts the range of polarisation cross-coupling levels found by measurements.

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References

1 IKEGAMI, F., YOSHIDA, S., TAKEUCHI, T., and UMEHIRA, M.: 'Propagation factors controlling mean field strengths on urban streets', *IEEE Trans.*, 1984, **AP-32**, (8), pp. 822–829

2 SIWIAK, K.: 'Radiowave propagation and antennas for personal communications' (Artech House, Norwood, MA, 1998), 2nd Edn.

3 TAGA, T.: 'Analysis for mean effective gain of mobile antennas in land mobile radio environments', *IEEE Trans.*, 1990, **VT-39**, (2), pp. 117–131

4 COX, D.C., MURRAY, R.R., ARNOLD, H.W., NORRIS, A.W., and WAZOWICZ, M.F.: 'Cross-polarization coupling measured for 800MHz radio transmission in and around houses and large buildings', *IEEE Trans.*, 1986, **AP-34**, (1), pp. 83–87

5 LEE, W.C.Y., and YEH, Y.S.: 'Polarization diversity system for mobile radio', *IEEE Trans.*, 1972, **COM-20**, (5), pp. 912–923