E. Distribution of the propagating power in curves

In the curved subway tunnel, a rapid decrease of the received power level at the inner side of a curve is observed. The measurement in the GSM900 band plotted in Fig. 4 was performed over the total length of the subway tunnel. As already indicated, the transmitting antenna and the receiving monopole were both situated on the right side of the tunnel axis referring to Fig. 3. Following the tunnel's course depicted in Fig. 2, the receiver was on the outer side in the left curve and, consequently, on the inner side in the following right curve at the end of the tunnel. The averaged measured path loss is plotted Fig. 13. At 850m to 950m from the transmitter, the curve is dropping by almost 8dB. This is the area of the right bend, with the receiver situated at the inner side of the curve.

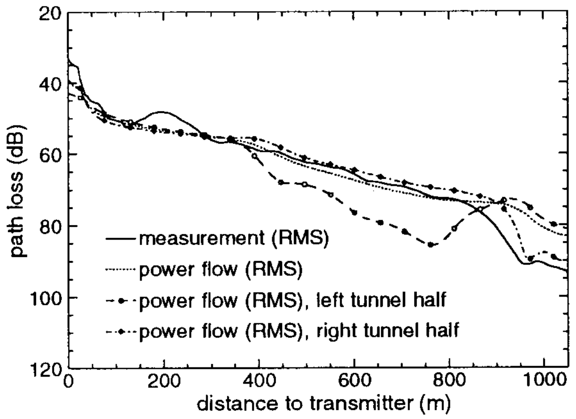

Fig. 13. Mean propagating power through the curved tunnel calculated by ray-tracing, compared to the averaged measurement of Fig. 4 at f_{GSM} = 945MHz (RMS window length: $200\lambda_0$)

In the same figure, the mean path loss predicted by ray-tracing is indicated by the dotted line. The mean path loss is obtained by summing the powers of the multipath components at the receiver instead of the respective complex voltages (also termed power-sum) [2]. Furthermore, the entire cross section is used as area of analysis, which speeds up the simulation time considerably [13]. Although the overall propagation slope is predicted very well, the defocusing effect can obviously not be predicted by this integral method. In order to detect such a shift of energy, the area of analysis is split. Instead of working on the total cross section of the tunnel, the method is now applied separately on the left and the right halves of the cross section. The power flux in the right half, shown by the curve with the black diamonds in Fig. 13, follows the measurement quite closely. Furthermore, the power flux in the left half is drawn in the figure. On the first 350m, where the tunnel is approximately straight, the energy is equally distributed on both sides of the tunnel. In the left curve (between 350m and 800m), the energy is focused on the right half of the tunnel. In the following right bend, the energy is shifted from the inner (right) side of the curve to the outer (left) side of the curve. The break-even point is at about 900m from the transmitter, after which most of the energy is gathered in the left tunnel half. This result again indicates the effect of curves on the propagation behaviour, and the requirement for an appropriate modelling approach.

IV. Conclusions

Comparing measurements and simulations of the EM-wave propagation in the Berlin subway, it was shown that the geometry of tunnels, especially the cross-sectional shape and curves, have a major impact on the propagation behaviour. In order to obtain accurate path loss predictions, it is mandatory to describe the special geometry of tunnels in propagation modelling adequately. It was also shown that the fast fading in tunnels cannot be characterized by standard analytical probability density functions over the entire range of values. The densities derived from propagation modelling provide a superior fit.

V. Acknowledgements

The authors would like to thank E-Plus, Germany and Mannesmann Mobilfunk, Germany for the provision of the measurement equipment and the Berlin Subway Carrier (BVG) for their support and assistance during the measurement campaign.

References

[1] D. Didascalou, M. Döttling, T. Zwick, and W. Wiesbeck, "A novel ray optical approach to model wave propagation in curved tunnels," in *IEEE Int. Vehicular Technology Conference (VTC'99-Fall)*, Amsterdam, The Netherlands, Sep. 1999, pp. 2313–2317.

[2] N. Geng and W. Wiesbeck, *Planungsmethoden für die Mobilkommunikation, Funknetzplanung unter realen physikalischen Ausbreitungsbedingungen*, Springer, Berlin, 1998, (in German).

[3] Y. Yamaguchi, T. Abe, T. Sekiguchi, and J. Chiba, "Attenuation constants of UHF radio waves in arched tunnels," *IEEE Transactions on Microwave Theory and Techniques*, vol. 33, no. 8, pp. 714–718, 1985.

[4] Y.P. Zhang and Y. Hwang, "Characterization of UHF radio propagation channels in tunnel environments for microcellular and personal communications," *IEEE Transactions on Antennas and Propagation*, vol. 47, no. 1, pp. 283–296, 1998.

[5] W.C.Y. Lee, *Mobile Communications Engineering*, McGraw-Hill, New York, 1982.

[6] R. Steele, Ed., *Mobile Radio Communications*, Pentech Press, London, 1992.

[7] ITU-R Rec. PN.1057, *Probability distributions relevant to radiowave propagation modelling*, International Telecommunications Union (ITU), Geneva, 1994.

[8] J.G. Proakis, *Digital Communications*, McGraw-Hill, New York, 2nd edition, 1989.

[9] R. Kattenbach and T. Englert, "Auswertung statistischer Eigenschaften von Impulsantworten zeitvarianter Indoor-Funkkanäle," *Kleinheubacher Berichte*, vol. 39, pp. 321–332, 1995, (in German).

[10] J.A. Nelder and R. Mead, "A simplex method for function minimization," *The Computer Journal*, vol. 7, pp. 308–313, 1964/65.

[11] M. Lienard and P. Degauque, "Propagation in wide tunnels at 2 GHz: A statistical analysis," *IEEE Transactions on Vehicular Technology*, vol. 47, no. 4, pp. 1322–1328, 1998.

[12] A. Papoulis, *Probability, Random Variables and Stochastic Processes*, McGraw-Hill, New York, 2nd edition, 1984.

[13] J.S. Lamminmäki and J.J.A. Lempiäinen, "Radio propagation characteristics in curved tunnels," *IEE Proceedings—Microwaves, Antennas and Propagation*, vol. 145, no. 4, pp. 327–331, 1998.