ickendorf"), which was built in the late 80's. The

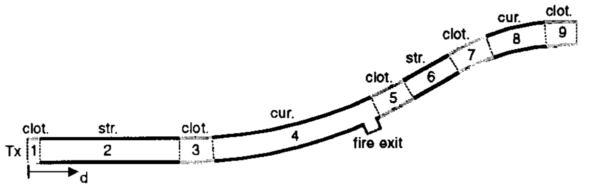


Fig. 2. Schematic course plot of the arched shaped tunnel (U8), with a total length of $l_{U8} \approx 1079$m

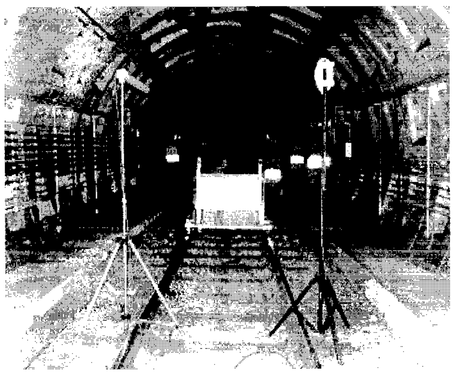

Fig. 3. View into the arched shaped tunnel (U8) of Fig. 2 from "Karl-Bonhoeffer-Nervenlinik" ($d = 0$m)

cross section of the arched tunnel is constituted by a circular shape of radius $r_{cs} \approx 2.9$m with an elevated floor 1.2m above the lowest point of the circle (cf. Fig. 3). A schematic plot of the tunnel's course is shown in Fig. 2. It consists of nine different sections and can roughly be described by a first straight part, followed by a left bend with large radius of curvature and a right bend with smaller radius of curvature. The total length of the tunnel is $l_{U8} \approx 1079$m, the maximum measured distance is $d \approx 1000$m. At distances $d > 420$m from the transmitter, the receiver and the transmitter have no longer a direct line-of-sight (LOS). At distance $d_{exit} = 620$m from the transmitter, an open connection (fire exit) exists for security reasons between the actual and the second tube, which runs in parallel, extending over an area of approximately 25m$^2$ (cf. Fig. 2). Figure 3 depicts the view into the tunnel from the station "Karl-Bonhoeffer-Nervenlinik", with the transmitters situated at the beginning of the tube.

It is apparent form Fig. 3, that the walls are not smooth but that they have a periodic structure due to the special construction by screwed prefabricated elements. Consequently, the occurring (large scale) height variations of the tunnel walls are not resulting from a statistically rough surface in a strict sense, but rather from a periodically rough surface[1]. Nevertheless, the concept of rough surface scattering can be applied in an approximate way by adapting the mean roughness of the walls with growing distances: at small distances from the transmitter, where most rays impinge under oblique incidence (i.e. with small incident angles) onto the walls, a mean roughness of $\sigma_h = 2$cm is assumed. At larger distances, where most rays impinge under near grazing incidence onto the walls, the mean roughness—and thus the attenuation—is increased (up to $\sigma_h = 15$cm), to reflect the shadowing behaviour of the special wall structure. The rail sleepers lie on gravel. The roughness of of the floor was estimated to $\sigma_h = 5$cm. The parameters of the building materials in the simulation correspond to dry concrete ($\underline{\varepsilon}_r = 5 - j\,0.1$). The roughness of the walls is taken into account by the modified Fresnel reflection coefficients [2].

[1]A periodically rough surface generally results in scattering patterns with specific preferential directions.

## III. Results

Several transmitting antenna constellations were measured and simulated at the two frequencies. To quantify the agreement of predictions and measurements, mean values $\mu_M$ and standard deviations $\sigma_M$ of the difference (in dB) between the measured and the predicted losses are determined. The values are either obtained by a direct "raw" comparison, indicated by the subscript $M$, or after a previous running root mean square (RMS) generation (cf. section III-D), indicated by the subscript $\bar{M}$ leading to $\mu_{\bar{M}}$ and $\sigma_{\bar{M}}$.

### *A. Path loss in the curved arched-shaped tunnel (U8)*

In the curved arched-shaped tunnel, several transmitter locations were deployed. Figures 4 and 5 depict the comparisons for the configuration shown in Fig. 3.

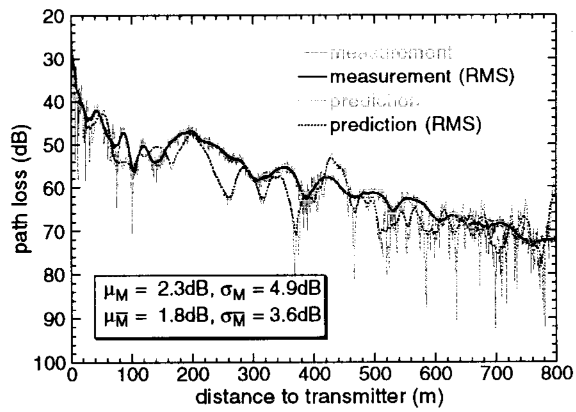


Fig. 4. Comparison of measurement and simulation at $f_{GSM} = 945$MHz, running RMS window length: $40\lambda_0$ (right transmitting antenna in Fig. 3)

The GSM900 antenna was situated at a height of $h_T = 2.5$m, 0.98m to the right of the tunnel's center (right transmitting antenna in Fig. 3). The GSM1800 antenna was positioned at $h_T = 2.45$m, 0.93m to the left of the center (left transmitting antenna in Fig. 3). The receiving antennas were aligned accordingly with the GSM900 monopole on the right side and the GSM1800 monopole on the left side of the lorry. The path loss was simulated by the RDN-based ray-tracing method. 150 million rays were traced with up to 40 reflections. The calculation time for the 1600 receivers was about 40h on a standard HP workstation. The good agreement of the measured and the predicted path loss validates the RDN modelling approach. The small