Path Loss, Scattering, and Multipath Delay Statistics in Four European Cities for Digital Cellular and Microcellular Radiotelephone

Scott Y. Seidel, Student Member, IEEE, Theodore S. Rappaport, Senior Member, IEEE, Sanjiv Jain, Michael L. Lord, Member, IEEE and Rajendra Singh

Abstract—This paper presents typical and worst case root mean square (rms) delay spreads, excess delay spreads (10 dB) and mean channel path loss at 900 MHz in four European cities using typical cellular and microcellular antenna locations. A power law propagation model is used to determine how the mean wide-band channel path loss changes as a function of distance between a base and a mobile. It is shown that a change in reference distance from 1 km to 100 m can change the perceived propagation power law exponent from 3.0 to 2.7, where free space propagation is assumed from the transmitter to the reference distance. The data reveal that for microcellular sites with low base antennas, rms delay spreads are less than 2 \( \mu \text{s} \) with excess delay spreads (10 dB) less than 6 \( \mu \text{s} \). When high base station antennas are used, rms delay spreads are generally less than 8 \( \mu \text{s} \) and excess delay spreads (10 dB) are less than 16 \( \mu \text{s} \). The worst case measurement with line-of-sight to the Frankfurt skyline produced a multipath component 7 dB below the direct component at an excess delay of 51.3 \( \mu \text{s} \). The worst case rms delay spread is 19.6 \( \mu \text{s} \). Radar cross sections (RCS) of common scatterers in cellular and microcellular radio channels are shown to range between \(-4.5\) and \(+5.7\) dBm².

1. INTRODUCTION

As cellular radiotelephone use increases, future cellular networks will be required to provide increased capacity with improved quality. It is predicted that there could be over 20 million cellular telephones in operation in the United States by 1995 [1]. Growth of the cellular industry in Europe with the 1992 Pan-European system is likely to equal or exceed that of the growth in the U.S. A digital GSM standard which uses slow frequency hopping and 270 kb/s time-division multiple-access (TDMA) channels has already been established and is being installed [2]. Present cellular systems typically cover radial distances of 1 to 8 km in urban areas, with three or four antenna sites per cell, depending on terrain, traffic density, and co-channel interference constraints. As digital cellular radio telephone systems evolve, further increases in the number of users will be accommodated by distributing communications into microcells which have smaller radii and power levels than today's typical cells [3], [4].

Much work has already been done to characterize UHF urban radio multipath channels by researchers worldwide (see [5] and references therein). These works have been valuable in assessing typical and worst case power delay profiles that describe the temporal extent of the multipath and the amplitudes of multipath components from reflecting objects. In [5], propagation measurements were made in four U.S. cities using a measurement system and data processing approach identical to that used in the present study. The results of [5] indicate that root mean square (rms) delay spreads are typically less than 4 \( \mu \text{s} \) in flat east coast cities and less than 12 \( \mu \text{s} \) in west coast cities which have small mountains. In those same cities, excess delay spreads (10 dB) are shown to be typically less than 17 \( \mu \text{s} \) on the east coast and 25 \( \mu \text{s} \) on the west coast. Distributions of the rms delay spread and excess delay (10 dB down) are given in [5].

In this paper, we provide results of a measurement campaign conducted during the summer of 1989 to provide a reasonable sample of (local worst case) multipath profiles and typical wide-band path loss characteristics in six typical future European digital cellular and microcellular radio sites in four German cities: Hamburg, Stuttgart, Dusseldorf, and Frankfurt [6]. These characterizations are required for determining limitations on multiple access techniques, and the impact that propagation and physical system layout has on co-channel interference and channel time dispersion at potential cellular and microcellular base station locations.

The measurements in this paper are based on a 500 ns baseband (4 MHz RF bandwidth) probing pulse. Since the probe has a bandwidth much greater than the coherence bandwidth of typical mobile channels, we call this a wide-band measurement. There are inherent differences between wideband (4 MHz RF bandwidth) and narrow-band (say RF bandwidth \( \leq 30 \) kHz) propagation. The instantaneous narrow-band received power undergoes rapid fluctuations due to Doppler-induced fast fading as the mobile moves. Wide-band signal levels do not display this rapid fading due to the inherent frequency diversity in the wide bandwidth signal. Path loss models based on a wide-band measurement technique are important for assessing co-channel interference and...
coverage levels in emerging spread spectrum mobile communication systems with bandwidths of several megahertz as opposed to current systems with channel bandwidths of 25-30 kHz. In this paper, we give descriptions of the six measurement locations and show recorded profiles at those locations, and use the relative frequency approach to probability to present statistical distributions of measured worst case time dispersion. We also provide measured wide-band propagation path loss data and quantify the severity of time dispersive channels at particular sites. The radar cross sections (RCS) for typical scatterers are deduced from the measurements.

II. THE MEASUREMENT APPARATUS AND PROCEDURE

The measurement apparatus is identical to that used in [5] except for a few slight differences. A 50 W peak, 942,225 MHz, 500 ns pulse modulated carrier was transmitted from the mobile at 200 µs intervals. The omnidirectional vertically polarized base and mobile antennas provide 6 and 3 dBi gain, respectively. The sensitive base receiver has a ~94 dBm noise floor over 4 MHz RF bandwidth.

Typical system and cable losses were 5 dB between the receiver antenna and the front end, and 3 dB between transmitter and antenna. The maximum path loss which could be measured by the system is 131 dB. The maximum receiver dynamic display range is 30 dB for any particular received power delay profile.

The mobile van continuously transmitted pulses as it traveled local roadways. As in [5], the measurements concentrated on extracting typical local worst case (in terms of time dispersion) measurements from typical operating locations. The base receiver recorded individual power delay profiles by time averaging the mobile transmission over a 1 s interval.

We classified the base stations as cellular or microcellular locations, depending on base station antenna height. Antenna heights for typical cellular base stations ranged from 40 to 93 m above ground level. Microcellular antenna heights were approximately 20 m above ground, which is at the upper end of the range of antenna heights envisioned by many for microcellular base sites [3], [4], [8], [9]. The mobile canvassed areas both inside and outside envisioned cell boundaries to provide insight into the relationship between path loss and distance. It is clear that as cells shrink in size, users in co-channel cells will be physically closer to the desired cell. Thus, co-channel interference and multipath propagation due to specular reflections from buildings, bridges, and other man-made structures will need to be characterized. Hence, the measurements give local worst case time dispersive characteristics, mean path loss, and scattering as a function of distance for cellular and microcellular radio channels.

The relative height of surrounding objects close to the base was used to distinguish cellular from microcellular base stations. Cellular base stations were located on the tallest building available and had a clear view to the distant surroundings in all directions. Microcellular base stations, due to the lower antenna heights, were surrounded by buildings and trees of comparable or greater height, and hence had smaller coverage areas.

III. CHANNEL MODEL AND IMPORTANT CHANNEL PARAMETERS

The channel model is in the form of a linear filter [5]. The low-pass output of an RF carrier modulated with a 500 ns sounding pulse closely approximates the baseband impulse response $h_b(t)$. As in [5], [10], instead of measuring the channel output $r(t)$, $|r(t)|^2$ was measured. Multipath delays within each profile were measured with respect to a first detectable signal arriving at $\tau_0 = 0$.

Wide-band multipath channels can be grossly quantified by their root mean square (rms) delay spread and excess delay spread (10 dB) (defined in [5]). In this work, as in [5], individual values of rms delay spread and excess delay spread (10 dB) are computed from the time average of 32 instantaneous snapshots of the power delay profile over a one second interval. This averaging is performed by the oscilloscope while the mobile transmitter was in motion. Absolute power measurements were made by referencing the oscilloscope voltage of received profiles to the peak oscilloscope voltage for calibration runs that used a known peak input signal power. Since a square-law detector was used, the oscilloscope voltage display corresponds to received power. Computation of channel path loss was achieved by computing the total area under each power delay profile [10]. Let $PL$ denote path loss in a received profile, $P_t$ denote peak transmitter power during measurements, $PCAL$ denote peak transmitted power for a calibration run, $A_r$ denote the receiver attenuation setting for the given measurement, and $ACAL$ denote the attenuation setting during calibration. Then, $PL$ is given by

$$PL[\text{dB}] = P_t[\text{dBm}] - PCAL[\text{dBm}] - A_r[\text{dB}] + ACAL[\text{dB}] + 10 \log_{10} \left( \frac{G_{CAL} \Delta \tau_{CAL}}{G_{t} \Delta \tau_{r}} \right)$$

where $P_t$ is +47 dBm, $\Delta \tau$ is the sample interval for the profile measurement, and $\Delta \tau_{CAL}$ is the oscilloscope sampling interval for the back-to-back reference measurements (9.7 ns). $G_{t}$ is the sum of the individual recorded oscilloscope values (in mV) for a measurement run that represents the relative received power in a power delay profile [10]. $G_{CAL}$ is the sum of the recorded oscilloscope values for a calibration run. Note that the antenna gains (9 dB), and the cable losses of the measurement system antenna feeders (8 dB) virtually cancel out and thus are not included in the computation of path loss in (1).

For each of the visually identifiable multipath components in the power delay profiles presented in this paper (Figs. 1–6), we have calculated the radar cross section (RCS) in dBm². These values are summarized in Table I. Since detailed terrain and building size information were not retained, we have made the following assumptions in order to determine representative values from measured profiles.

1) All multipath components are assumed to be caused by a single scattering source, which may be due to either a single large object (building) or group of objects in the channel. We assume that no paths are scattered more than once.

2) The scatterer is modeled by an RCS such that the
TABLE I
SHADOWING OF DIRECT SIGNAL IN DECIBELS AND CALCULATED RADAR CROSS SECTION IN dBm² OF EACH MULTIPATH COMPONENT IN Figs. 1–6

<table>
<thead>
<tr>
<th>Profile</th>
<th>Excess Delay (μs)</th>
<th>Shadowing (dB)</th>
<th>RCS (dBm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamburg</td>
<td>0.0</td>
<td>3.3</td>
<td>16.6</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>−4.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>−2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>−0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>5.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.0</td>
<td>17.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8.0</td>
<td>6.3</td>
<td></td>
</tr>
<tr>
<td>Bank Building</td>
<td>0.0</td>
<td>14.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>−2.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>−0.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.0</td>
<td>5.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17.0</td>
<td>42.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>17.5</td>
<td>16.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>18.0</td>
<td>14.1</td>
<td></td>
</tr>
<tr>
<td>Kronberg 1</td>
<td>0.0</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>70.0</td>
<td>55.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>72.0</td>
<td>29.6</td>
<td></td>
</tr>
<tr>
<td>Kronberg 2</td>
<td>0.0</td>
<td>29.3</td>
<td>17.2</td>
</tr>
<tr>
<td></td>
<td>51.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A. Overview

In Hamburg, the receiver was located downtown, and the mobile traversed roads that were typically 3–4.5 km outside of town. The antenna height was 40 m on top of the 11-story Mannesmann office building. This cellular base location was surrounded by several four- to eight-story apartment buildings.

Fig. 1 shows a typical power delay profile measured with the receiver located in Hamburg, and the transmitter located 6.9 km away on Kohlbrandbrucke highway, on the south side of the Elbe River. Fig. 1 shows the actual received peak power of a measurement run and is identical in nature to those shown in [5], except in [5], the power delay profile of the calibration runs were presented in scaled form so that the integrated power of the probing pulse was assigned to the known peak power of the input. The only difference between power profiles presented here and those in [5] is that the true RF peak power in [5] can be found from the displayed profiles by adding $10 \log(500 \text{ ns}/40 \text{ ns})$, or 11 dB.

Fig. 1 is typical of measurements made along open areas, such as a bridge or overpass, within a small city. The line-of-sight component is the dominant signal, and scatterers appear specular and are easy to identify from topographical maps. The possible locations of scatterers which induce a constant time delay radio path form an ellipse with the transmitter and receiver at the foci. Thus, it is possible to distinguish the probable locations of scattering objects, assuming a multipath signal scattered only once. The strong multipath component at 1.5 μs excess delay (which corresponds to 450 m excess travel distance) is deduced to be from the city skyline with a RCS of +16.6 dBm². Table I summarizes the calculated RCS values for each of the visually identifiable multipath components in the power delay profiles presented in Figs. 1–6. Also in Table I is the amount of shadowing for the first arriving component, which is computed as the difference between the observed path loss in the first arriving component and the theoretical free space path loss for the given T-R separation. Since Hamburg is not surrounded by large mountains, no components arrive in this profile with excess delays greater than 3 μs. All multiple paths must be from reflections off nearby objects. Since the only major reflectors are buildings and bridges located within 2 km of the transmitter and receiver, it is not possible to receive multipath components with excess delays greater than 7 or 8 μs, hence, the largest observed rms delay spread in Hamburg was 2.7 μs and 99% of the excess delays (10 dB) were less than 6 μs.

In Stuttgart, the base receive antenna was located at a height of 23 m at a typical suburban microcellular site (a six-story building). The receiver site was 4 km south of downtown with a coverage range of up to 6.5 km. Northward, toward downtown Stuttgart, are many six to ten-story buildings, single family homes, and open farm land. The buildings surrounding the receiver were slightly taller than the base. Two side-by-side 20-story buildings were located 5 km away from the receiver and hills which rose several hundred feet above the urban terrain were located 10 km away to the northeast. The mobile transmitter traveled road-
ways flanked with four-story office and residential buildings both in the northern suburbs and east of the receiver, in the vicinity of the 20-story buildings. Coverage to the west was limited to distances less than 1.5 km due to a neighboring obstructing building.

RMS delay spreads in suburban areas of Stuttgart were almost always less than 2 μs, with the worst case value being 5.4 μs. Late arriving components are due to reflections from surrounding buildings. Occasionally, reflections at 4 μs were observed and are believed to be from the 20-story buildings. Even reflections from the large buildings do not cause unusually large rms delay spreads; hence, microcellular radio channels in suburban Stuttgart appear relatively tame. In very few cases, reflections down 13 dB from the LOS signal were detected from the hills located 10 km away from the receiver.

One typical cellular base station in downtown Dusseldorf had an antenna 88 m high on top of a 23-story office building surrounded by several buildings of comparable height. East of the site is a high rise apartment building, and a downtown business district which consists of many four-story office buildings. Many measurements were made with the mobile traveling on large bridges that cross the Rhine River which snakes throughout the city.

Fig. 2 shows a worst case profile measured in Dusseldorf. During rush hour traffic, the transmitter traversed a narrow street flanked by the Rhine River and five-story buildings. The narrow streets tend to duct RF energy from large facades which are visible to the receiver. This profile shows a multipath component having received power as large as the direct component at 7 μs excess delay and is typical of worst case conditions for a mobile operating in an urban commercial district which contains large buildings. The equivalent single scatterer which causes this multipath component has an RCS of +17 dBm². While this profile exhibits an rms delay spread slightly greater than 3 μs, rms delay spreads measured in urban areas were generally less than 3 μs.

Measurements were made at three receiver locations in Frankfurt, a large metropolitan market with a noticeable skyscraper cluster. A typical microcellular base station location was on top of the PA building. This five-story office building was surrounded by many taller buildings and large trees which caused the measurement range to be less than 1.5 km.

As the mobile traversed downtown Frankfurt, worst case rms delay spreads were recorded to be 2.9 μs and worst case excess delays (10 dB) were 7.1 μs, similar to those measured in Hamburg, Stuttgart, and Dusseldorf. Measurements at the PA building show that in some parts of Frankfurt, microcellular multipath radio channels are relatively tame. It is likely that shadowing by surrounding buildings and trees cause severe path attenuation for non-line-of-sight propagation paths. This limits the excess delay of components that can be detected by the receiver.

A typical cellular receiver location in Frankfurt was the Bank building which is located less than 1 km from the PA building in the downtown financial district. The base station was a 93 m tall office building surrounded by several buildings of similar or greater height. The Rhine River was less than 2 km away and is about 1 km wide. Mobile operations for the Bank building tests were primarily east and south of the receiver within a 3–4 km range, in a dense urban area with six-story tall apartment buildings. Several locations were measured out to 6.5 km and were later revisited by the mobile with the receiver at the Kronberg base location.

Fig. 3 illustrates a worst case profile with the receiver at the Bank building and the transmitter on the other side of the Rhine River. In addition to several distinct paths which arrive within the first 5 μs, there is a cluster of multipath components at 17 to 18 μs, one with an amplitude larger than the direct component. These components are due to reflections from two outlying buildings on the east perimeter of Frankfurt, which are about 3.5 km away from the Bank building. Fig. 4 shows a map of Frankfurt near the Bank building. The solid circles indicate the locations of the base and mobile for the received power delay profile in Fig. 3. The outlying 10-story (= 50 m) tall buildings that rise above the surroundings along the east perimeter of Frankfurt are shown on the right side of Fig. 4. The radar cross sections of these buildings vary from +14.1 to +42.9 dBm² as shown in Table I. The profile illustrates how specular reflections from
buildings can cause rms delay spreads much larger than are usually observed.

The Kronberg apartment building, at the base of a mountain 13 km north of Frankfurt, was another typical cellular base station location. The surrounding area was clear from obstructions except for a similar building a few hundred meters to the east. Rolling hills were to the north and west, and mountains to the south. Both the base and mobile had unobstructed views of the Frankfurt skyline at most Kronberg locations.

Reflections from surrounding mountains and the downtown Frankfurt skyline caused the worst case measurements shown in Figs. 5 and 6. In Fig. 5, the mobile was 3 km away with LOS to both the receiver and the city skyline. The figure indicates a distinct multipath component at 70 μs excess delay having an amplitude only 11 dB down from the LOS signal. There also is a specular reflector which induces a component 20 dB down from LOS at an excess delay of 4 μs.

These reflections can be modeled by radar cross sections of +55.7 and +4.4 dBm², respectively.

If the direct and the 70 μs component undergo free space propagation, then theory dictates that the 70 μs component would be at least 28 dB down from LOS. It is shown in [5] and [13] that if the direct component obeys worse than free space propagation and the delayed component obeys free space propagation, then the delayed component can have power within an order of magnitude of the direct component at excess delays greater than 100 μs. Figs. 7(a) and 7(b) show a map of the Kronberg base location. The solid circles in Figs. 7(a) and 7(b) indicate the base and mobile locations for the received power delay profiles shown in Figs. 5 and 6, respectively. The location denoted Mobile70 in Fig. 7(a) is where the multipath component with an excess delay of 70 μs was observed. Fig. 6, with a multipath component at 51.3 μs, was recorded with the mobile at the location denoted by Mobile51 in Fig. 7(b). The 70 μs components in Fig. 5 and the 51 μs component in Fig. 6 correspond to the time delays...
required for a signal to reach the receiver from the transmitter via a reflection from the skyscrapers in downtown Frankfurt. The large RCS of $+55.7 \text{ dBm}^2$ can be considered the RCS of a combination of building facades in the downtown area.

Measurements with the base near the Kronberg apartment building illustrate that in general, rms delay spreads are limited to a few microseconds; 95% of the rms delay spreads at this location are less than 1.5 $\mu$s. However, when the base and mobile have line-of-sight to outlying scatterers such as the Frankfurt skyline and surrounding mountains several kilometers away, rms delay spreads as large as 19 $\mu$s can be observed with strong late-arriving components. This illustrates the importance of considering man-made objects in the design and implementation of emerging high-capacity wireless systems.

B. Statistical Results of Time Dispersion and RCS

Rms delay spread and excess delay spread (10 dB down from peak signal level) cumulative distribution functions (CDF’s) have been compiled based on the experimental data. After threshold screening, we have a data pool of over 3800 multipath power delay profiles which represents worst case channels for typical cellular and microcellular markets. In general, since these measurements have focused on the collection of local worst case power delay profiles, overall time dispersive channel characteristics are likely to be somewhat tamer than are portrayed by these data.

Fig. 8 provides the CDF of excess delay spread (10 dB) which indicates the likelihood that no multipath components will be within 10 dB of the strongest component for excess delays larger than a given excess delay. Fig. 8 provides overall statistics based on the combination of data from all six measurement locations. The maximum observed excess delay of a multipath component with an amplitude within 10 dB of the maximum signal level was 51.3 $\mu$s.

Fig. 9 illustrates the CDF of rms delay spread for the entire data ensemble. The worst case value is 5.4 $\mu$s for the receiver locations in Hamburg, Stuttgart, and Dusseldorf. These cities are not surrounded by mountains, and are very similar to cities on the east coast of the U.S., hence, the rms delay statistics are similar to Washington, D.C. and Greenbelt, MD [5]. The overall worst case rms delay spread was found to be 19.6 $\mu$s (Fig. 6).

These data indicate that, in general, the measured West German cities are not quite as time dispersive as the cities which were measured in the U.S. [5]. One explanation is that in the U.S. measurement program, the west coast cities had substantial hilly and mountainous terrain within close range of the receiver sites. In the present measurement campaign, no city had such a high degree of undulating terrain. Representative operating locations, such as major highways, bridges, and urban and suburban districts were chosen in both cases, however, each measured city is physically very different, and the time dispersive data displayed by a channel is very much specific to the exact operating location. The Mansell Street location in San Francisco [5], which yielded excess delay spreads of 100 ps, was found during the last day of experiments. It may very well have not been discovered, in which case the worst case statistics for [5] and this present study would have been nearly identical.

Previous measurements in European and other cellular and microcellular markets indicate that rms delay spreads in markets similar to the cities measured here are small [4], [5], [12], [14]-[16]. In [4], delay spreads were shown to nearly always be less than 1 $\mu$s in both cellular and microcellular environments. Delay spreads were shown to be less than 1 to 2 $\mu$s in [12] and [14]. In [15], rms delay spreads were shown to be less than 2.5 $\mu$s for urban environments and less than 5
μs for hilly and mountainous regions. In mountainous regions, multipath components can have excess delays as large as 30 μs [16].

For cellular and microcellular markets such as Hamburg, Stuttgart, and the PA building in Frankfurt, rms delay spreads are almost always less than a few μs. In built-up urban markets such as Dusseldorf and the Bank Building in Frankfurt, rms delay spreads are 3 to 4 μs. However, when large, distant scatterers are illuminated by tall base antennas, rms delay spreads as large as 8.3 μs are seen. In locations like the Kronberg apartment building near Frankfurt, multipath components can arrive with excess delays as large as 51 and 70 μs. Such large values of excess delay cause rms delay spreads to be as large as 19 μs. Designers of digital cellular and microcellular systems must consider the potential of outlying scatterers to cause severe time dispersion and interference. This study as well as [5] and [13] show that multipath components can arrive with excess delays much greater than 30 μs.

These data confirm that in cellular and microcellular urban areas, rms delay spreads are limited to about 2 or 3 μs because of partitioning by city streets. Suburban and rural cellular locations with high antennas which have a clear view of large buildings and mountains simultaneously, can give much larger delay spreads. The data also show the effect building facades can have, and point to the applicability of radar cross section modeling for the study of time dispersion. Furthermore, these data illustrate the usefulness and ease of implementation of a time domain multipath measurement system for locating sources of multipath interference. With a rotatable directive antenna and a detailed map which includes building locations and sizes, the measurement system used here could effectively sound a city for optimal site locations. This could replace the current method of narrow-band RSSI indications which cannot give information on the time dispersion of radio channels. This would be particularly useful for installation of digital cell sites as the operator could "look for large delays" as the mobile traverses roads in the coverage area.

Since all measurements represented in the figures have concentrated on local worst case situations, it stands to reason that European digital cellular systems will encounter slightly tamer channels than are portrayed here. With a data rate of 270 kilobits/s, equalization will be the key aspect in performance of the GSM digital radio link. For BT = 0.3 and an average irreducible bit error rate of 10^{-2}, the critical rms delay spread to symbol period ratio is 0.1 for unequalized operation in certain simulated channels [17]. This means that without equalization, in such channels the GSM system can only tolerate an rms delay spread of less than 1 μs. Even in cities where terrain is flat such as Stuttgart and Hamburg, rms delay spreads exceeding 1 μs 6% of the time. In areas with large rolling hills and huge buildings, such as Frankfurt, rms delay spreads exceed 1 μs, 10 to 20% of the time. With rms delay spreads larger than 1 μs such a large percentage of time, the system performance will be highly dependent upon equalizer performance.

Only at locations like Kronberg or the Bank building in Frankfurt, where unusually large scatterers are illuminated (mountains, buildings or bridges), do rms delay spreads exceed 10 μs. It is suggested that in these rare locations, special precautions should be used to reduce co-channel interference and time dispersion regardless of multiple access technique used. Useful techniques to mitigate multipath and co-channel interference are suggested in [5].

The RCS of typical objects that can scatter RF energy are given in Table I, and vary from −4.5 to +55.7 dBm^2. In [12], RCS values were shown to be +10 to +20 dBm^2 for typical suburban obstacles, and as large as +42 dBm^2 for large buildings. It is possible that the multipath component in Fig. 2 which resulted in a radar cross-section of −4.5 dBm^2 is actually due to a shadowed scatter path where the physical radar cross-section is larger than −4.5 dBm^2. A more detailed study which models the RCS as a function of incident and scattered angle would be useful for propagation prediction tools that could be used to design digital cell site locations using maps that include man-made structures.

C. Path Loss

From (1), the actual wide-band received power in each measured power delay profile was calculated. Received power
can be modeled relative to the power received at a reference location \(d_o\) m away from the transmitter. Scatter plots of path loss versus distance have been computed for each measurement site and for all the data in order to provide insight into the behavior of received power as a function of base receiver location, surrounding terrain, and distance. The average path loss model and the standard deviation (\(\sigma\)) about the model for each base location and all the data, have been computed in a manner described below which is similar to [18].

For an isotropic source, the received power \(P(d)\) at some distance \(d\) meters away from the source can be related to a reference power \(P_o\) received at a reference distance \(d_o\) away from the source by the expression

\[
P(d) = P_o \left( \frac{d_o}{d} \right)^n, \quad d > d_o.
\]

In (3), if \(n = 2\), the radio wave propagates as in free space. Typical urban and rural mobile radio channels have \(n\) values which range from 2.2 to 4.35 when measured with a narrow-band receiver [19], [20]. If we assume free space path loss from the transmitter antenna to the reference distance \(d_o\) away from the transmitter and antenna gains (9 dB) nearly offset the system losses (8 dB), then the free space loss from the transmitter to \(d_o\) is

\[
P_o [\text{dBm}] = P_o [\text{dBm}] + 20 \times \log_{10} \left( \frac{\lambda}{4\pi d_o} \right).
\]

For \(d_o\) equal to 100 m, \(P_o\) is 71.9 dB down from the transmitted power \(P_t\). For \(d_o\) equal to 1 km, \(P_o\) is 91.9 dB down from \(P_t\). While a reference distance of \(d_o = 1\) km has traditionally been used for large cellular systems [21], emerging microcellular systems have a large number of users closer than 1 km to the base. A two-ray (direct and ground reflected) propagation model shows that a \(d^4\) power decay occurs for users several km away from the base, but a shift in the reference distance from 1 to 0.1 km for the theoretical two-ray model changes the perceived mean power decay from \(d^4\) to \(d^{2.5}\) [22]. For emerging microcellular communication systems where many users are less than 1 km from the cell, a 1 km reference distance seems pointless. Since we have several measurements that have T-R separations between 0.1 and 1 km, we used a 0.1 km reference distance. To demonstrate the effect of a 1 km reference distance, we present the results for the entire data set with both reference distances and discuss the results.

For the heavily shadowed Frankfurt, PA building microcellular site, the thick solid line in Fig. 10 shows the best linear regression fit to the data and indicates that average wide-band path loss increases as distance to the 3.8 power. The path loss law curves, shown as thin solid lines for \(n = 1, 2, 3, 4\) and 5, are computed by assuming that antenna gains = system losses and that path loss is referenced to a free space propagation distance (\(d_o\)) of 100 m from the transmitter. Each circle represents a single power delay profile and the vertical axis is absolute path loss. The PA Building is classified as a typical microcellular base location, although we do not observe characteristics which lead to the double-regression path loss model seen in [8] and [9].

The overall path loss exponent for all measurement locations is given in Fig. 11 to be \(n = 2.7\). However, when the reference distance \(d_o\) changed from 100 m to 1 km, the best linear fit, as shown in Fig. 12, became \(n = 3.0\). This demonstrates the importance of leverage points (i.e., free space reference distance) in developing propagation path loss models when using (3). Figs. 11 and 12 are plotted with the same horizontal axis to facilitate comparison between the two figures. Notice that in Fig. 12, the free space path loss line is drawn to a T-R separation of 1 km before the path loss models for different \(n\) values diverge as T-R separation increases. This dependence of propagation power law on reference distance indicates that care must be taken to select a reference distance appropriate to the system design [22].

In [8] and [9], the propagation models were developed without a specific reference distance. For example, the linear regression model in [9] is of the form path loss = \(a + b \times \log\) (distance). The parameters \(a\) and \(b\) were varied to determine the best fit to the data. However, the value \(a\) is essentially the path loss at a specific reference distance which is different for different data sets. The advantage of the models presented here is that a physically explainable (free space) received power level at a specific reference distance is used.

The measurements presented here used a wide band technique to determine the channel path loss at each particular mobile location by integrating the area under each power delay profile and converting the value to actual received power (in dBm) based on a calibration run with a known received power as shown in (1). This is different from conventional work which used narrow-band receivers and computed path loss from actual received signal strength. With a wide-band characterization technique and a close-in reference distance, path loss exponents can have values less than three, as opposed to values close to four for CW models that assume only a direct and ground reflected path, and use a reference distance of 1 km. Indeed, for studying the effects of cellular and microcellular channels on wide band multiple
access techniques such as CDMA, a wide band measurement technique must be used. The effect of the reference distance \( d_o \) has been shown to be significant in determining the power law exponent. Table II summarizes the statistics of the measured data for each of the different base receiver locations and the ensemble statistics for reference distances of 100 m. The path loss exponent \( n \) is largest for the two microcellular sites. This is expected since with lower antenna heights, there is more shadowing due to objects between the base and mobile. The mobile traversed areas which exceed probable microcell boundaries to give insight into the path loss between potential co-channel cells. With a larger path loss exponent \( n \), cells may be placed closer together to increase frequency reuse efficiency. In heavily built-up urban areas such as Frankfurt, additional microcells with low antenna heights such as that at the PA building may be installed to increase system capacity without significantly increasing co-channel interference in a properly designed system.

V. CONCLUSION

This paper has presented results of a propagation measurement campaign which explored the path loss and time dispersive characteristics of 940 MHz cellular and microcellular mobile radio channels in Europe. Several thousand power delay profile measurements were made at six typical cellular and microcellular base station locations in four German cities. The data were obtained at local worst case time dispersion locations over hundreds of kilometers of typical operating routes, such as highways, bridges, and city streets, and have formed the basis for statistical models which can be used to predict the percentage of locations or the percentage of time in which channels will possess particular values of rms delay spread, and excess delay spread (10 dB). Radar cross sections (worst case) given in Table I ranged from \(-4.5 \, \text{dBm}^2\) to \(55.7 \, \text{dBm}^2\). The effect of reference distance \( d_o \) on wide-band path loss and the propagation path loss laws for six cellular and microcellular radio channels are given.

ACKNOWLEDGMENT

The thoughtful comments of the reviewers, which helped improve the quality of this paper, are appreciated.

REFERENCES

Mr. Seidel is a member of Tau Beta Pi, Eta Kappa Nu, and Phi Kappa Phi.

S. Y. Seidel (S’89) was born in Falls Church, VA, in 1986. He received the B.S. and the M.S. degrees in electrical engineering from Virginia Polytechnic Institute and State University, Blacksburg, in 1988 and 1989, respectively. He is pursuing the Ph.D. degree in electrical engineering at Virginia Polytechnic Institute and State University under the support of an NSF Graduate Research Fellowship. Since 1989, he has been a member of the Mobile and Portable Radio Research Group at Virginia Tech. He has been involved in the development of both urban microcellular and indoor radio channel models and is interested in propagation prediction and system design.

Mr. Seidel is a member of Tau Beta Pi, Eta Kappa Nu, and Phi Kappa Phi.