

# Statistical Characterization of Urban Spatial Radio Channels

Martin Toeltsch, *Student Member, IEEE*, Juha Laurila, *Member, IEEE*, Kimmo Kalliola, Andreas F. Molisch, *Senior Member, IEEE*, Pertti Vainikainen, *Member, IEEE*, and Ernst Bonek, *Senior Member, IEEE*

**Abstract**—We present a statistical analysis of wideband three-dimensional channel measurements at base station locations in an urban environment. Plots of the received energy over azimuth, elevation, and delay planes suggest that the incident waves group to clusters in most measured transmitter positions. A super-resolution algorithm (Unitary ESPRIT) allows to resolve individual multipath components in such clusters and hence enables a detailed statistical analysis of the propagation properties. The origins of clusters—sometimes even individual multipath components—such as street apertures, large buildings, roof edges, or building corners can be localized on the city map. Street guided propagation dominates most of the scenarios (78%–97% of the total received power), while quasi-line-of-sight over-the-rooftop components are weak (3%–13% of the total received power). For this measurement campaign, in 90% of the cases, 75% of the total received power is concentrated in the two strongest clusters, but only 55% in the strongest one. Our analysis yields an exponential decay of power with  $8.9 \text{ dB}/\mu\text{s}$ , and a standard deviation of the log-normally distributed deviations from the exponential of 9.0 dB. The power of cross-polarized components is 8 dB below copolarized ones on average (vertical transmission).

**Index Terms**—Multipath channels, radio propagation, mobile radio channel, spatial channel modeling, smart antennas, clusters.

## I. INTRODUCTION

ADAPTIVE antennas (AA) will be a major factor for the successful introduction of third-generation wireless systems like Universal Mobile Telecommunication System

(UMTS) [1]–[4]. For the design, performance evaluation, and cell planning with AAs, we need realistic spatial channel models [5], [6]. Three-dimensional (3-D) measurements are required for parameterization and validation of such channel models.

Despite this importance, only few spatial measurements are available, see [7] and references, therein. Furthermore, all existing high-resolution measurements at the base station (BS) use at most two dimensions, e.g., delay and azimuth [8]. In [9]–[11] wideband 3-D measurements at the mobile station (MS) at street level are reported (down-link measurements). We present here results and analyzes of a 3-D measurement campaign at the BS, i.e., delay, azimuth, and elevation, and—additionally—polarization. The paper focuses on the statistical evaluation of the data. Details about the measurement setup, the urban environment, as well as sample results and their physical interpretation, are given in [12] and [13]. The evaluation is based on up-link wideband directionally resolved channel measurements in urban macro- and micro-cells in downtown Helsinki, Finland.

Section II introduces the basic concept of array processing, our measurement equipment, and the prerequisites of the synthetic aperture technique. Section III describes the environment of the locations, identifies the propagation phenomena, and gives some sample results of the evaluation. In Section IV, we describe and discuss the statistical analysis, finally Section V summarizes this paper.

## II. MEASUREMENT SETUP

To determine the parameters of the incident waves, we used a wideband channel sounder together with a planar antenna array. The measurements were performed by the Institute of Digital Communications (IDC) of the Helsinki University of Technology (HUT) in cooperation with the Institut für Nachrichtentechnik und Hochfrequenztechnik (INTHF) of Technische Universität Wien with the IDC wideband channel sounder [14] utilizing a switched multiplexing principle introduced in [15]. The center frequency was 2154 MHz, the measurement bandwidth was 100 MHz. The transmitter sent a PN-sequence with 255 chips continually, i.e., starting the same sequence again immediately after the end of the last one. The chip frequency of the transmitter was 30 MHz, the sampling frequency of the analog-to-digital converter was 120 MHz, from which follows that each chip was four times oversampled at the receiver. It used a pseudo noise (PN)-sequence correlation technique for the determination of the impulse response. Hence, the delay range is  $255/30 \text{ MHz} = 8.5 \mu\text{s}$  with a resolution of  $1/30 \text{ MHz} = 33 \text{ ns}$ .

Manuscript received March 15, 2001; revised August 31, 2001. This paper was presented in part at the IEEE VTS 53rd Vehicular Technology Conference, Spring 2001, May 6–9, 2001, Rhodes, Greece.

M. Toeltsch is with the Institut für Nachrichtentechnik- und Hochfrequenztechnik (INTHF), Technische Universität Wien (TU-Wien), Vienna A-1040, Austria (e-mail: Martin.Toeltsch@ieee.org).

J. Laurila was with the Institut für Nachrichtentechnik- und Hochfrequenztechnik (INTHF), Technische Universität Wien, Vienna, Austria. He is now with the Nokia Research Center, Radio Communications Laboratory, Nokia Group, Helsinki FIN-00045, Finland (e-mail: juha.k.laurila@nokia.com).

K. Kalliola was with Helsinki University of Technology, Institute of Digital Communication, Radio Laboratory, Espoo, Finland. He is now with the Nokia Research Center, Radio Communication Laboratory, Nokia Group, Helsinki FIN-00045, Finland (e-mail: kimmo.kalliola@nokia.com).

A. F. Molisch was with the Forschungszentrum Telekommunikation Wien (FTW) Vienna, Austria and Institut für Nachrichtentechnik und Hochfrequenztechnik (INTHF), Technische Universität Wien, Vienna, Austria. He is now with the Wireless Communications Research, AT&T Labs—Research, Middletown, NJ 07748 USA (e-mail: afm@research.att.com).

P. Vainikainen is with the Institute of Digital Communications (IDC)/Radio Laboratory, Helsinki University of Technology, Espoo FIN 02015 HUT, Finland.

E. Bonek is with the Institut für Nachrichtentechnik und Hochfrequenztechnik (INTHF), Technische Universität Wien (TU-Wien), Vienna, Austria and also with the Forschungszentrum Telekommunikation Wien (FTW), Vienna A-1040, Austria (e-mail: Ernst.Bonek@nt.tuwien.ac.at).

Publisher Item Identifier S 0733-8716(02)03549-7.

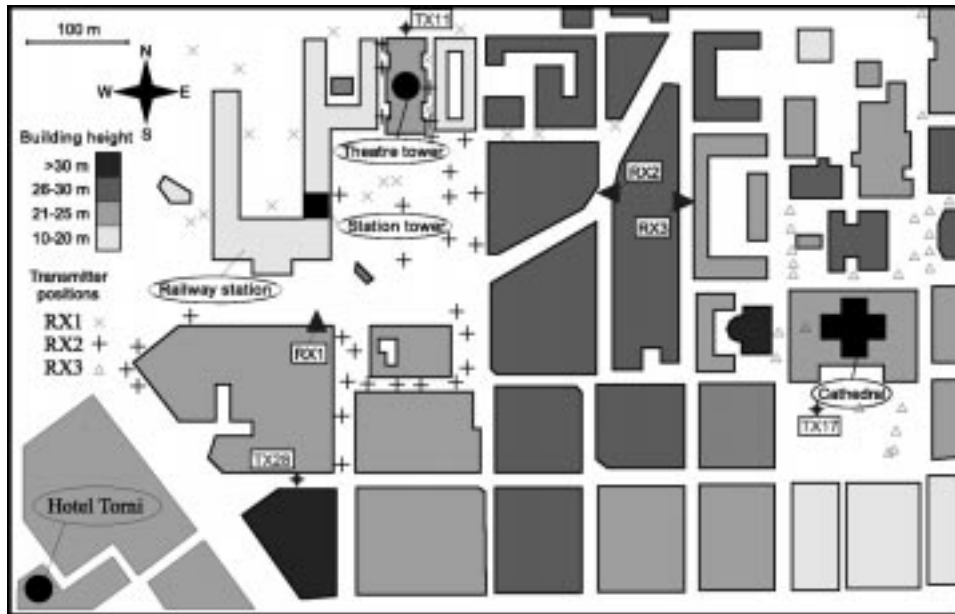


Fig. 1. Overview about the measurement area with all 3 RX sites, TX-positions of the sample plots are marked.

The transmit antenna at the MS was a vertically polarized omnidirectional disc antenna. The vertical 3-dB beamwidth was  $87^\circ$ , the transmit power 40 dBm. Approximately 80 different transmitter positions were investigated.

The receiving BS was located at one of three different sites below, at, and above the rooftop level (RX 1–RX 3, cf., Fig. 1). A 16-element physical array with dual polarized  $\lambda/2$ -spaced patch antennas was combined with a synthetic aperture technique to build a virtual two-dimensional (2-D) antenna structure. The patches were linearly polarized at  $0^\circ$  (horizontal direction) and  $90^\circ$  (vertical direction). With these  $16 \times 62$  elements we are able to resolve the direction of arrival (DOA) of incoming waves both in azimuth (horizontal angle) and elevation (vertical angle) by using the super-resolution Unitary ESPRIT algorithm [16]–[18]. Note that the number of antenna elements limits the number of identifiable waves, but not the angular resolution of the method. Together with a delay resolution of 33 ns, we are able to characterize the radio channel in all three dimensions separately for the two polarizations. An excellent overview about array signal processing—including estimation of the DOAs and a comparison of ESPRIT with other algorithms—can be found in [19].

One prerequisite for the applicability of the synthetic aperture technique is that the radio channel is static during the whole data collection period. The time for one complete measurement was 14.5 s. We tested the impact of moving cars by performing several measurements at the same position with and without traffic. The traffic caused variations of up to 20% of the angular power spectrum, whereas, two consecutive measurements without traffic only showed 5% variation. From that, we can conclude that the repeatability is very good in the absence of traffic, and that the impact of moving objects can be shown and also be quantified. To avoid problems, the whole procedure was done at night with minimum traffic conditions.



Fig. 2. View from RX 1 site (microcell).

### III. PROPAGATION ENVIRONMENTS

#### A. Description of Environment

We performed the measurements in an urban environment in downtown Helsinki, Finland, in June and October 1999. The three receiver locations (RX 1–3) are marked in Fig. 1 by triangles pointing in broadside direction of the array. The photos of the Figs. 2–4 have the same viewing direction. Fig. 1 also informs about all the corresponding TX positions. The location RX 1 (height  $h_{RX} = 10$  m) was a typical microcell site below the rooftop height of the surrounding buildings, and we performed measurements with 20 different TX positions. RX 2 (height  $h_{RX} = 27$  m) was at the rooftop level, and we investigated 32 TX positions. RX 3 (height  $h_{RX} = 21$  m) was a typical macrocell BS position above rooftop heights, and we

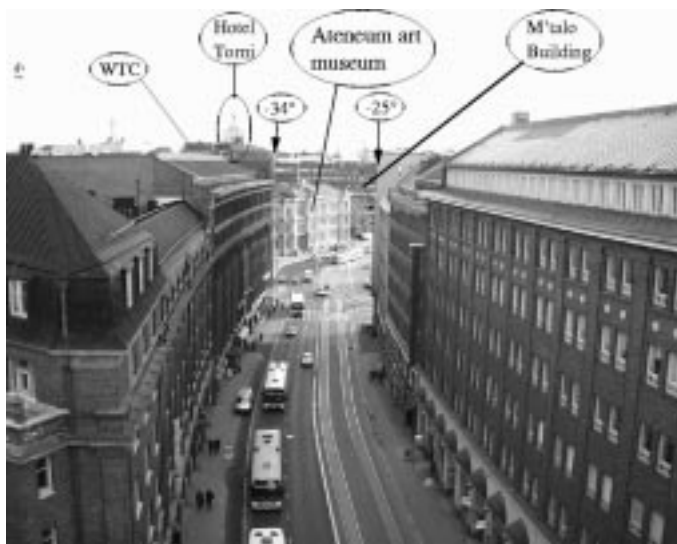


Fig. 3. View from RX 2 site (macrocell).



Fig. 4. View from RX 3 site (macrocell).

measured at 27 TX positions. More information on the locations and the environment can be found in [12]. Note that even if we are talking about macrocells (RX 3), the distances between transmitters and the receiver were still below 500 m.

1) *RX 1*: Characteristic for this site is the wide and open square in front and slightly to the right of the array (Rautatien-tori). The square is surrounded by relatively high buildings<sup>1</sup> that are intersected by alleys and narrow streets. To the front left of the antenna is the large railway station, the entrance is at an azimuth  $\varphi \approx -40^\circ$ . The station tower directly in front of RX 1 at  $0^\circ$  is the highest building in the vicinity. Behind the railway station is a large railway yard. Fig. 2 shows a view from RX 1 to the square.

2) *RX 2*: The view from RX 2 shows the dominating street canyon of the broad Kaisaniemenkatu approaching the receiver from the left at  $-30^\circ$  (see Fig. 3). On the other end of the street is

<sup>1</sup>Most of them have four floors.

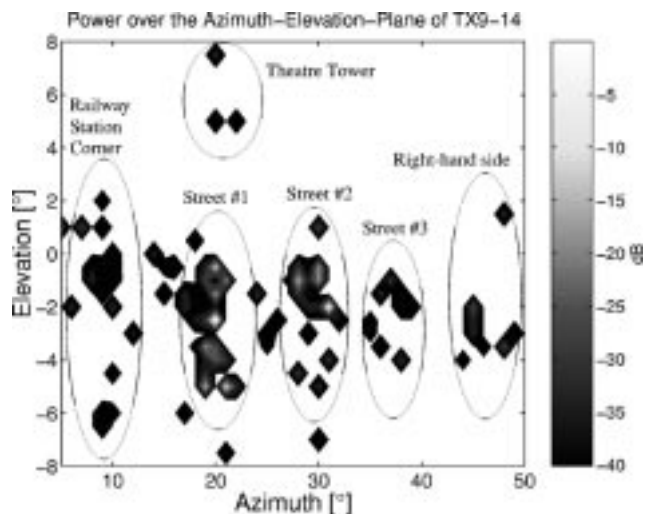


Fig. 5. Azimuth-elevation plane, sum of the powers of the copolarized and cross-polarized component of TX 9–14.

the large Rautatien-tori square (cf., Section III-A1), where electromagnetic energy is easily coupled into the street canyon. The height of this RX site is at the rooftop level of the surrounding houses. In several directions high rise buildings and towers can be seen (line-of-sight (LOS) from RX 2 to them), e.g., Theatre Tower, White Tower (cf., Fig. 2), Hotel Torni, World Trade Center (WTC), Makkaratalo building (M'talo).

3) *RX 3*: Although the height of RX 3 is lower than that of RX 2, it is an above-rooftop-site, as the buildings in front are significantly lower. The dominating Lutheran Cathedral with its metallic dome at  $\varphi \approx 40^\circ$  to the right acts as a strong scatterer, see Fig. 4. South of the cathedral is a large square (Senate Square) without LOS to the receiver.

## B. Sample Results

In this section we show some graphical results of the DOA estimation with Unitary ESPRIT. The power of the multipath components is calculated by means of a beamforming algorithm. From the approximately 80 transmitter positions, we choose representative ones, where several different propagation mechanisms become obvious. We mark concentration of strong multipath components by black ellipses and denote the objects (e.g., Street Canyon, Theatre, . . .) that originate them.

Note that the plots show the sum of the powers in horizontal and vertical polarization. Due to the continuously transmitting MS, the delay can only be interpreted as a relative distance between multipath components. The TX-positions used in the sample plots are marked in Fig. 1. TX 11 stands for the positions TX 9–14, which are all near TX 11.

1) *TX Position TX 9–14 (RX 1)*: These TX positions were located in the street canyons behind the large square about 300 m distant from the receiver array (RX 1), see also the photo in Fig. 2 (Street #1, Street #2). Fig. 5 shows the received power at the BS site RX 1 over the azimuth-elevation plane. The plot is color-coded, the brighter the color the stronger the power of incident waves. The minimum size of the “diamonds” corresponding to an individual wave has been chosen for optimum visibility in the plot. It is not related to the angular resolution!

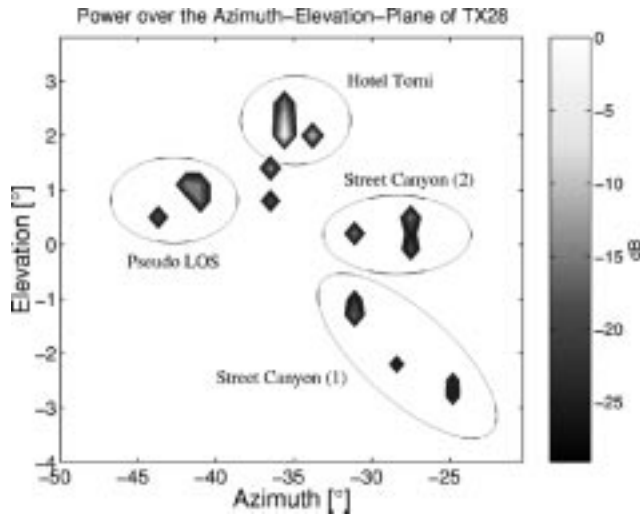


Fig. 6. Azimuth-elevation plane, sum of the powers of the copolarized and cross-polarized component of TX 28.

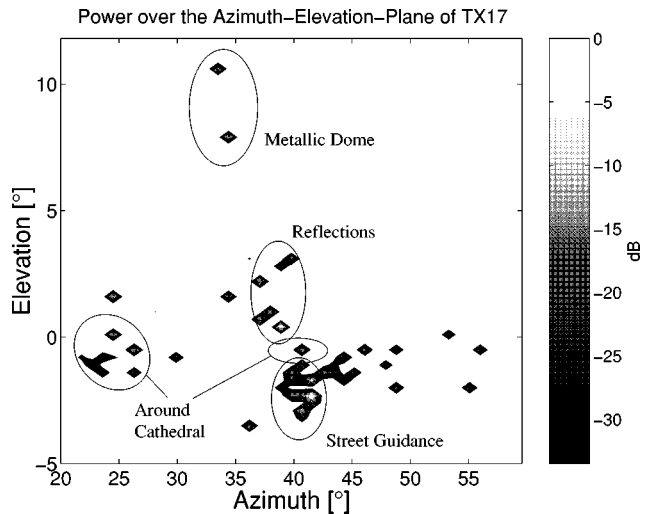


Fig. 8. Azimuth-elevation plane, sum of the powers of the copolarized and cross-polarized component of TX 17.

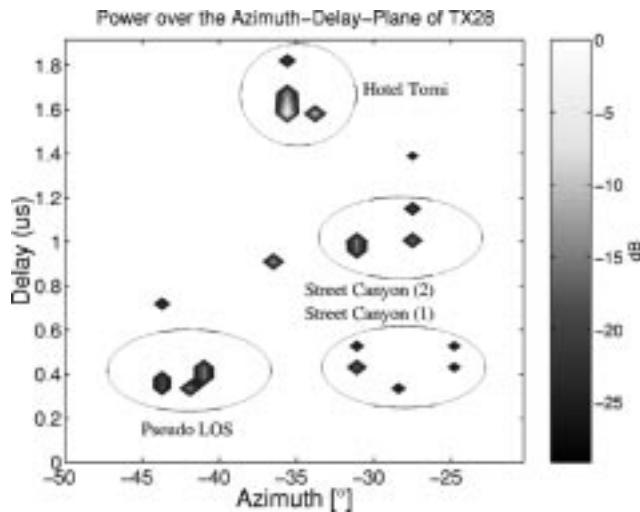


Fig. 7. Azimuth-delay plane, sum of the powers of the copolarized and cross-polarized component of TX 28.

The power of both the horizontal and the vertical components of the six transmitter positions (TX 9–TX 14) is summed up. This averaging gives a better picture of the propagation from a (small) area than by one TX position alone.

We can observe that the energy is concentrated in clusters that correspond to objects in the surrounding. Different propagation mechanisms also became evident, e.g., street-guided propagation (Street #1, #2, and #3), reflection on high-rise buildings (Theatre Tower), diffraction at the edge of a wall (Railway Station Corner), or scattering on surrounding buildings on the right-hand side of the square after street guidance (right-hand side).

2) *TX Position TX 28 (RX 2)*: TX 28 is situated behind a large block at a distance of 420 m from the receiver (RX 2), so there is no LOS from the transmitter to the receiver, but there is a LOS-connection from the transmitter to the Hotel Torini, which in turn has LOS to the receiver array at the azimuthal angle of  $\varphi \approx -36^\circ$ .

Figs. 6 and 7 show the power over the azimuth-elevation and azimuth-delay planes, respectively. In the delay domain we

identify 3 parts. The first components arrive from the direction of the transmitter over the rooftop ( $-41^\circ / +1^\circ$ , azimuth/elevation) (Pseudo LOS) with some weaker components coming also from the street canyon in front of the array (Street Canyon (1)). The second component is also coupled into the broad Kaisaniemenkatu street, but with a delay of  $0.6 \mu\text{s}$  and an elevation of  $0^\circ$  (Street Canyon (2)). The higher elevation indicates that these waves are apparently diffracted over the roof of the Ateneum art museum at the end of the Kaisaniemenkatu street (cf., Fig. 3). The last component is a reflection from the Hotel Torini ( $-35^\circ / 2 \dots 3^\circ$ ), and it carries about 8 dB more power than the other components.

We again observe a strong grouping of waves into clusters. At the position of these clusters in the azimuth-elevation-delay domain, important objects like street canyons or large buildings can be identified.

3) *TX Position TX 17 (RX 3)*: TX 17 is located on the Senate Square south of the large cathedral, 240 m from the receiver (RX 3); there is no LOS to the receiver.

We show azimuth-elevation and azimuth-delay plots in Figs. 8 and 9, respectively. There is no early component from the direction of the transmitter ( $56^\circ$ ), the first wave is seen in the direction of a street crossing (Street Guidance). A reflection from the metallic dome of the cathedral (Metallic Dome) arrives with a short delay.  $0.6 \mu\text{s}$  (180 m) after the first waves, there are several reflections from the houses behind the square, where the cathedral blocks the energy in the azimuthal range  $28 \dots 40^\circ$  (Around Cathedral, Reflections).

### C. Some Comments About Propagation

In Section III-B, we show that it is possible to identify many single (particular, different) multipath components, impinging at the receiver from different directions. But these components are not randomly distributed in the spatial and temporal domain, they naturally group to clusters. These clusters can be associated with objects in the environment due to the high angular and temporal resolution of our evaluation. (Sometimes even individual waves, within a cluster, can be associated with scattering

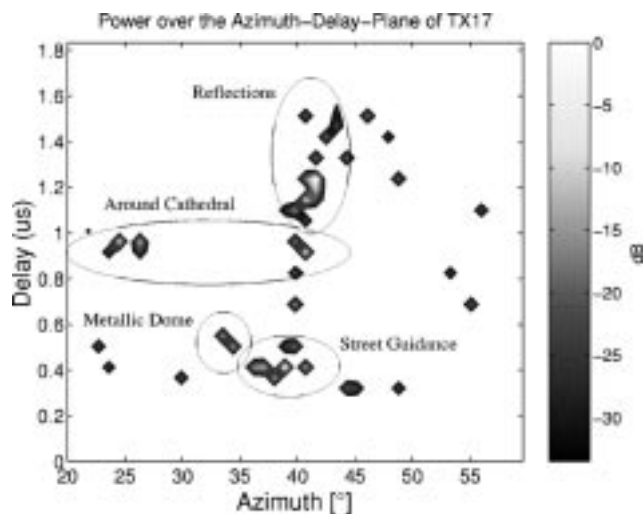


Fig. 9. Azimuth-delay plane, sum of the powers of the copolarized and cross-polarized component of TX 17.

objects.) The identification of such clusters is facilitated by inspection of the maps of the environment.

We define a cluster as a group of waves whose delay, azimuth, and elevation at the receiver are very similar, while being notably different from other waves in at least one dimension. Additionally all waves inside a cluster must stem from the same propagation mechanism.

We note at this point that the definition of clusters always involves a certain amount of arbitrariness. Even for mathematically “exact” definitions, arbitrary parameters (e.g., thresholds or number of components) must be defined. Clustering by human inspection, supported by maps of the environment, seems to give the best results.

We calculated the received power within each cluster (cluster power) by means of Unitary ESPRIT and a following beam-forming algorithm. The results were plotted in the azimuth-elevation-, azimuth-delay-, and elevation-delay-planes, samples can be seen in Section III-B. According to the obvious propagation mechanism, we assigned each clusters to one of three different classes.

*Class 1) Street-Guided Propagation:* Waves arrive at the receiver from the street level after traveling through street canyons. A typical example is the broad Kaisaniemenkatu street of RX 2.

*Class 2) Direct Propagation—Over the Rooftop:* The waves arrive at the BS from the rooftop level by diffraction at the edges of roofs, either directly or after reflection from buildings surrounding the MS. The azimuth mostly points to the direction of the transmitter with some spread in azimuth and delay. As an instance of Class 2, TX 10–TX 20 at RX 3 (west and south of the cathedral, all close to TX 17 in Fig. 1) can be mentioned.

*Class 3) Reflection From High-Rise Objects—Over the Rooftop:* The elevation angles are near the horizon, pointing at or above the rooftop. The waves undergo a reflection at an object rising above the average building height before reaching the BS. The azimuth shows the direction of the reflecting building, the delay is typically larger than for Class 1 or Class 2. One example for such a reflector is the Lutheran Cathedral at RX 3.

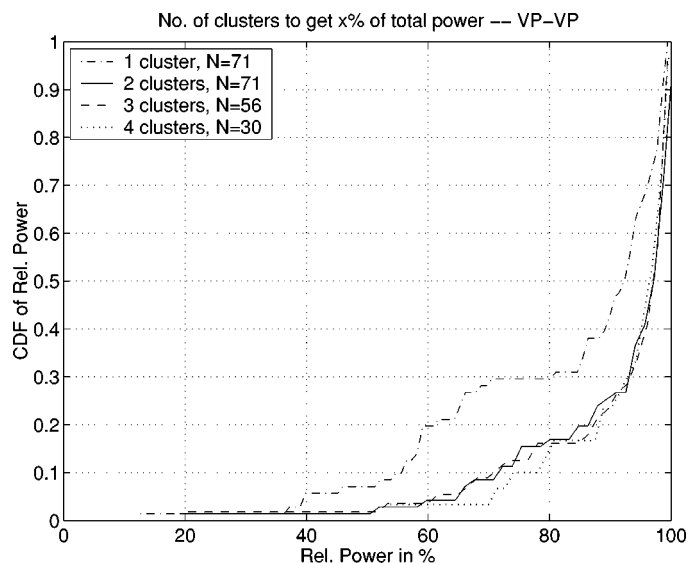


Fig. 10. CDF of the relative power for 1–4 clusters, all TX positions, transmitter and receiver vertically polarized (VP-VP).  $N$  is the number of samples.

The sum of the powers of all clusters belonging to the same class is called class power. In some cases the propagation history is a mixture of different classes, e.g., street guidance followed by diffraction at rooftops. We allocated such clusters to the class of the final path to the BS.<sup>2</sup>

#### IV. STATISTICAL ANALYSIS

In Section III, we showed by several sample plots that the waves received by the BS emanate from concentrated clusters. These clusters are present in the delay, as well as in the azimuth and elevation domains.

In the current section, we present some statistical evaluation to substantiate and quantify the clusterization. We will investigate: 1) the number of clusters that is required to get a specific percentage of the total power; 2) the powers of the clusters versus the delay; 3) the cross polarization discrimination (XPD) versus the delay; 4) the relative class powers; and 5) the distribution of the number of clusters. Such questions are important for designing algorithms for adaptive antennas, e.g., should one capture, in uplink, the power of one or more clusters; or, in downlink, how to distribute the available transmit power to which directions?

##### A. Cumulative Distribution Function (cdf) of Relative Power

We sorted the clusters of each TX position in descending order of their received power. After that, we calculated the ratio of the strongest-cluster power to the total received power; then the same for the sum of the first two clusters, the first three clusters, and so on. To generate a cdf of the relative power, we combined the results of all TX positions. Fig. 10 shows the cdf of the relative power for one to four clusters for the case of vertical polarized transmitted and vertical polarized received signals (VP-VP). In Fig. 11 the same is plotted for the horizontal

<sup>2</sup>Double-directional channel measurements [20] allow the tracing of up to three reflections or diffractions.

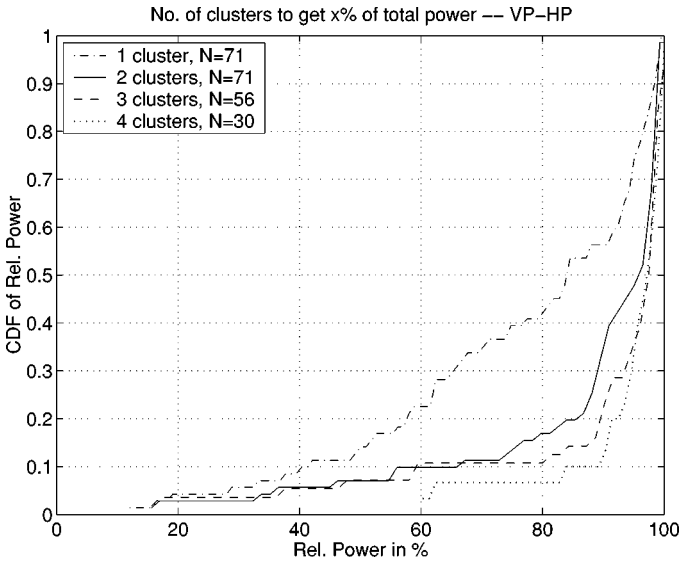


Fig. 11. CDF of the relative power for 1–4 clusters, all TX-positions, transmitter vertically and receiver horizontally polarized (VP-HP).  $N$  is the number of samples.

TABLE I  
AVERAGE RELATIVE POWER IN dB (RELATION OF CLUSTER POWER TO TOTAL RECEIVED POWER  $P_{tot}$ ) OF THE STRONGEST CLUSTER OF RX 1, RX 2, and RX 3, AND THE RATIO IN %

RX	VP-VP dB (% of $P_{tot}$ )	VP-HP dB (% of $P_{tot}$ )
1	-0.9 (81%)	-1.2 (76%)
2	-0.4 (91%)	-0.6 (87%)
3	-1.3 (74%)	-1.8 (66%)

(cross) polarized received component (VP-HP).<sup>3</sup> In the legends, we specify the number of samples the cdfs are based on.

First, we answer the question, how many percent the power of the strongest cluster contributes to the total power. If we refer to the 10% level in the cdf, Fig. 10 (11) says that in 90% of all cases the power in the strongest cluster is at least 55% (40%) of the total power. The average power of all strongest clusters of the measurements is 0.8 dB (copolarized) and 1.1 dB (cross-polarized) below the total power, that is 83.2% and 77.6% of the total power. The average extent of the strongest cluster is  $23^\circ$  ( $10^\circ$ ) in azimuth (elevation); the corresponding standard deviation is  $18^\circ$  ( $5.5^\circ$ ). Pointing a single beam—whose beam width has to match this extent—to capture the strongest cluster only, means losing about 2.6 dB or less of the available power in 90% of the cases. The average loss is only 0.8 dB. Note that the average size of a cluster is in general different from the intracenter spread [21]. Table I shows the average attenuation of the strongest cluster separately for the RX-sites. In particular at RX 2, the energy is exceedingly concentrated inside the strongest cluster (91% and 87% of the total received power) due to the guidance of Kaisaniemenkatu street's aperture.

Secondly, we analyze the contribution of the two strongest clusters. If we refer again to the 10% level in the cdf, Fig. 10 says that now 75% of the received, vertical power VP-VP is concentrated in the two strongest clusters, whereas the residual 25% is

<sup>3</sup>Note that the transmitter always sent vertically polarized.

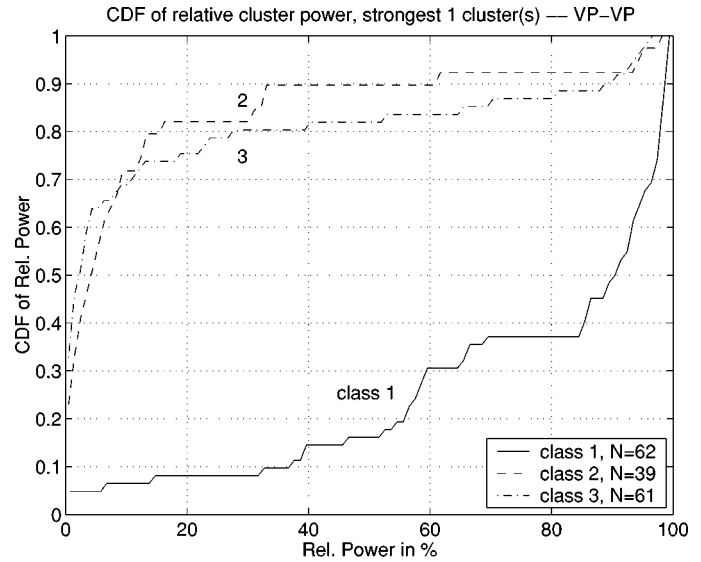


Fig. 12. CDF of the relative power for the strongest cluster separated by classes, all TX-positions.  $N$  is the number of samples.

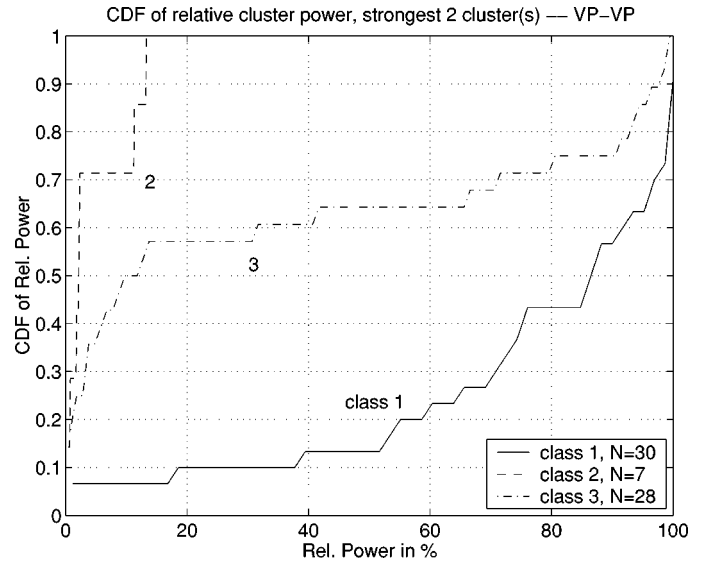


Fig. 13. CDF of the relative power for the two strongest clusters separated by classes, all TX-positions.  $N$  is the number of samples.

not concentrated in clusters anymore. It does make a difference to employ one or two clusters, but not more. For the cross-polarized component VP-HP the collected power increases to 60% if we use the two or three strongest clusters. With four clusters, 90% of the total power can be captured. The difference between two, three, and four clusters vanishes for higher levels of the cdf (85%–92% at a cdf-level of 0.2).

Finally, we compare the relative importance of the three classes defined in Section III-C. Figs. 12–14 show the cdf of their relative power. We only show the VP-VP case. Again, we specify the number of samples the cdfs are based on in the legends. We recognize the importance of class-1 clusters (street-guided propagation). In 50% of all class-2 and class-3 clusters the relative power is less than 10%, even for the sum of the three strongest clusters of each TX-position. Note that the separation into the three classes for the three strongest clusters (Fig. 14) yields only few samples for the corresponding

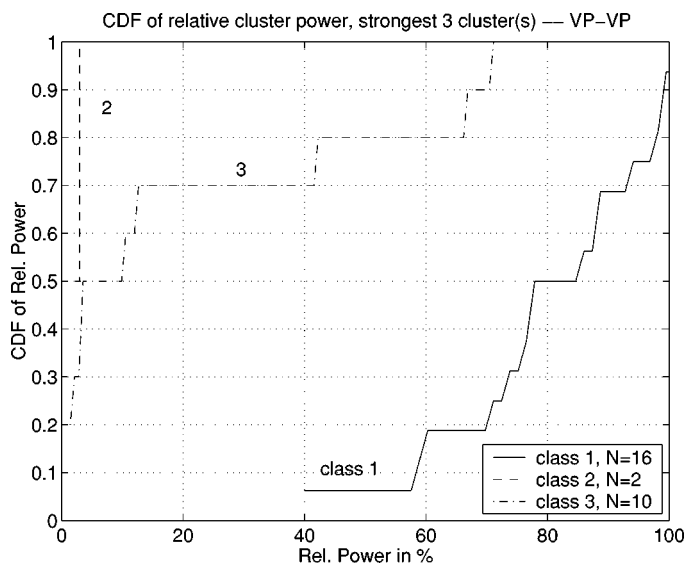


Fig. 14. CDF of the relative power for the three strongest clusters separated by classes, all TX-positions.  $N$  is the number of samples.

cdf and, hence, it is not very smooth anymore. Nevertheless, what can be observed is that there are far less class-2 clusters (direct over the rooftop) than class-1 or class-3. Moreover, the contribution of class-2 clusters to the total power is in all cases almost negligible compared to the other classes.

Our investigation reveals that: 1) significant power comes from narrow angle ranges (clusters) and 2) there are several such clusters present. Especially the more important copolarized waves VP-VP are concentrated by at least 75% in the two strongest clusters ( $-1.2$  dB of the total power).

### B. Cluster Powers versus Delay

We assigned each cluster its mean delay and related its cluster power to the total received power of the corresponding TX-position to get the cluster attenuation. The mean delay is the power-weighted average of the excess-delays of all multipath components in the cluster. The mean delay values of the clusters are always given relative to the mean delay of the first clusters, i.e., we assign a delay of  $\tau = 0$  ns to the first cluster. The quantity of interest is the relationship between cluster power and delay. Simple propagation models postulate an exponential law [22]. In analogy, we define  $P_i \propto ae^{-\tau_i/b}$ , where  $P_i$  is the linear power of cluster  $i$  ( $P_i$  not specified in dB!) and  $\tau_i$  is the delay of cluster  $i$ .  $a$  and  $b$  are model parameters, where  $b$  denotes the mean power decrease per delay unit and  $a$  is the average of the powers at zero delay (quasi-line-of-sight (LOS) components). We estimated the parameters  $a$  and  $b$  by a least-squares (LS) fit of the exponential law to the measured powers. The Appendix describes this estimator. The Figs. 15 and 16 show the scatter plot of (attenuation, delay)-tuples. The total number of clusters were 255 and 233, respectively. All calculations are done with linear powers; on the other hand, for visualization we prefer a logarithmic scale of the figures. By that we demonstrate two different interesting results. 1) These figures also show the LS fit to an exponential, which appears as a linear line in the logarithmic scale. We emphasize that it is different from a linear regression between the powers in dB and

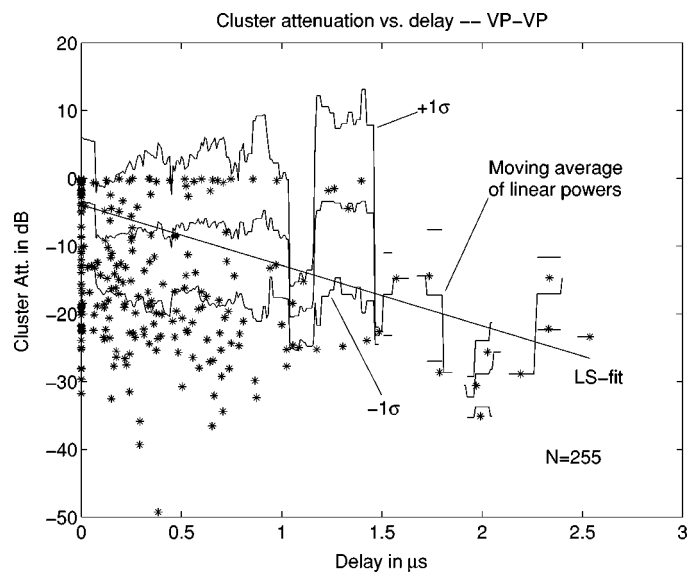


Fig. 15. Relation of the cluster power to the total power versus delay, all TX-positions, copolarization.  $N$  is the number of clusters.

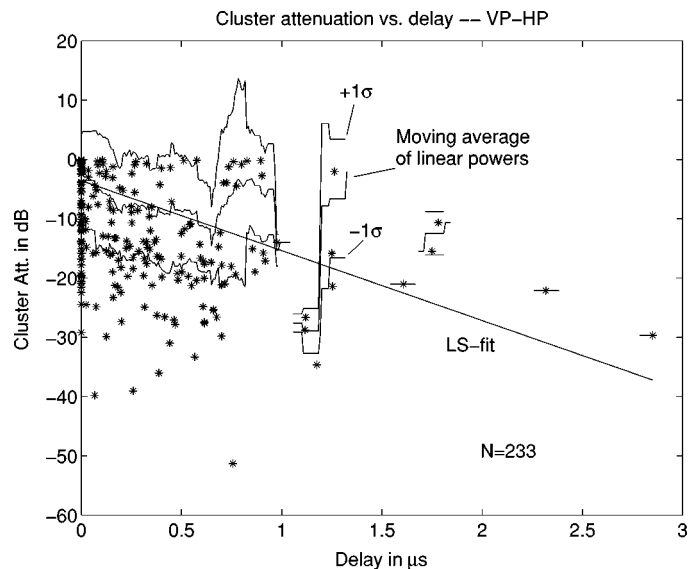


Fig. 16. Relation of the cluster power to the total power versus delay, all TX-positions, cross polarization.  $N$  is the number of clusters.

TABLE II  
THE MODEL PARAMETERS  $a$  AND  $b$  FOR BOTH RECEIVED POLARIZATIONS (VP AND HP) AVERAGED OVER ALL AVAILABLE CLUSTERS. THE TRANSMITTER WAS VP

	VP-VP	VP-HP
$a$	$-3.9\text{dB}$	$-3.6\text{dB}$
$b$	$8.9\text{dB}/\mu\text{s}$	$11.8\text{dB}/\mu\text{s}$

the delays. The slope of this line—corresponding to the model parameter  $b$ —explains the decreasing power of the clusters with increasing delay. Table II shows the parameter values for  $a$  and  $b$ . 2) Furthermore, we show the moving average of the linear cluster powers in a  $\pm 67$  ns delay window and the standard deviation  $\sigma_v$  of the estimation error  $v$  in the delay window in a distance of  $\pm 1\sigma$  from the power average (the mathematical definitions of  $v$  and  $\sigma_v$  are also given in the Appendix). We define

TABLE III  
AVERAGE DELAY OF THE STRONGEST CLUSTER OF RX 1, RX 2, AND RX 3

RX	av. delay VP-VP $\mu\text{s}$	av. delay VP-HP $\mu\text{s}$
1	0.068	0.071
2	0.38	0.28
3	0.11	0.048

$\sigma_v$  as the standard deviation of the logarithmic estimation error in dB. This estimation error was found to be log-normally distributed and up to a delay of about  $1 \mu\text{s}$ ,  $\sigma_v$  is independent of the delay  $\tau$ . The value of  $\sigma_v$  is 9.0 dB and 10.0 dB (co- and cross-polarization), respectively, averaged over the first microsecond. After  $1 \mu\text{s}$  there are too few clusters to draw reliable conclusions. Neither the moving average nor the standard deviation are plotted in sections where there are too few data samples, e.g., at  $\tau \approx 1.5 \mu\text{s}$  in the horizontal case (VP-HP). The averaged attenuation of all shortest delayed clusters corresponds to the parameter  $\alpha$  of Table II.

The cumulative distribution function of the delay of all strongest clusters shows that, in 60% of the cases, it is the quasi-LOS component that carries the largest power. The remaining 40% of the clusters is equally distributed between 0 and  $1 \mu\text{s}$  excess delay. The first cluster is not necessarily the strongest one. The mean values of the delays of those clusters that carry the strongest co- and cross-polarized energy are 0.21 and  $0.15 \mu\text{s}$ , respectively. In Table III, we summarize the average delay values separately for each RX-site. Whereas the excess path length of the strongest cluster of RX 1 and RX 3 (compared to the first cluster) is in the order of 15–30 m, it is more than 100 m in the case of RX 2. This corresponds well to the length of the broad Kaisaniemenkatu street (120 m) in front of the receiver array. The first components are from the quasi-LOS direction, but in contrast to RX 1 and RX 3, only few of them carry large power. The strongest waves are coming through the street aperture and have an excess delay corresponding exactly to the length of the street!

### C. XPD versus Delay

The XPD is defined as the ratio of the received power of the copolarized component to the power of the cross-polarized component, evaluated for each cluster. Instead of approximating the linear values as done in Section IV-B, we applied the linear least-squares estimate of the logarithmic XPD in dB to equally weight positive and negative values. The linear regression of the XPD in dB versus the delay should again give information about the correlation between the two variables. In Fig. 17, each XPD-value is marked by an asterisk at its corresponding delay. The number of clusters in this figure is  $N = 215$ . The linear regression has a slope of  $1.4 \text{ dB}/\mu\text{s}$ , hence, with increasing delay the copolarized component VP-VP gets stronger compared to the cross-polarized component VP-HP. Again, we also plot the moving average of the XPD in a  $\pm 67 \text{ ns}$  delay window and the upper and lower  $\pm 1\sigma$  standard deviation curve. Here,  $\sigma$  is the standard deviation of the measured XPD-data from the linear regression line. It significantly reduces from about  $\pm 10 \text{ dB}$  below

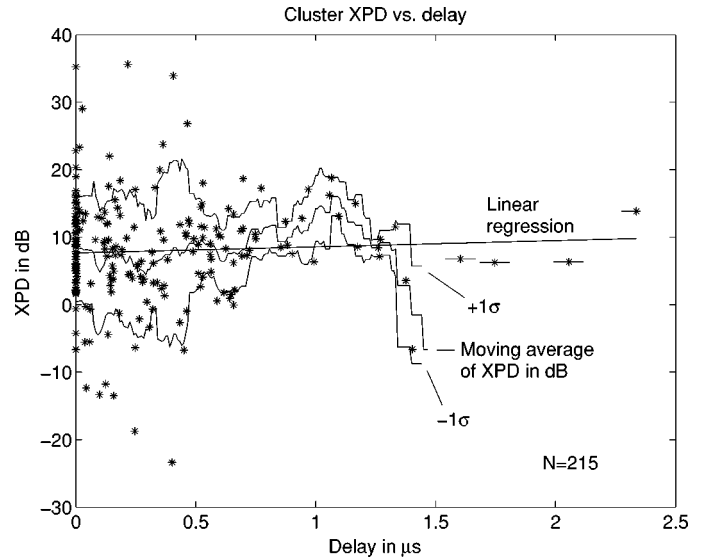


Fig. 17. XPD versus delay, all TX-positions.  $N$  is the number of clusters.

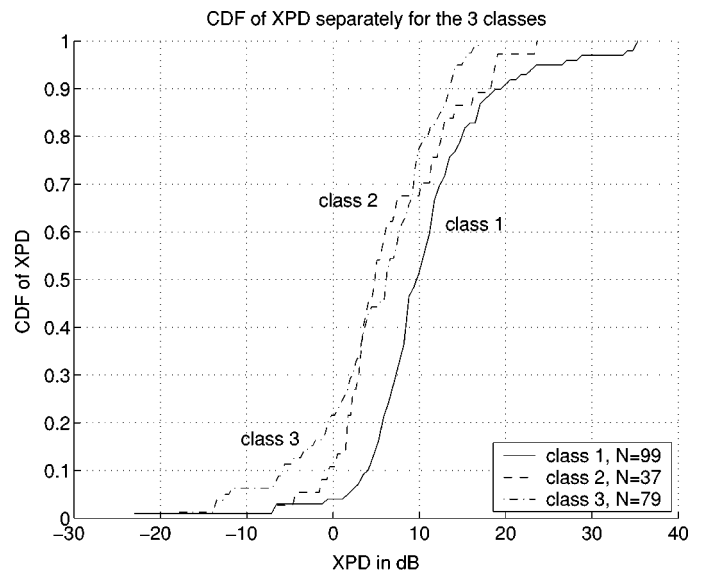


Fig. 18. CDF of the XPD separately for the three classes.  $N$  is the number of clusters.

$\tau = 0.5 \mu\text{s}$  to  $\pm 3 \text{ dB}$  above  $\tau = 0.5 \mu\text{s}$ . I.e., with increasing delay the XPD increases, and the samples are strongly concentrated around their average. In most of the cases (89%) the vertical component is much stronger than the horizontal, the average of all XPD-values is 8.0 dB.

In Fig. 18, we show the cdf of the XPD separately for the three different classes 1–3 (cf. Section III-C). The legend also denotes the number of clusters in the corresponding classes. The XPD of all class-1 clusters (street-guidance) is on average 5 dB greater than the class-2 (over the rooftop) and class-3 clusters (far reflections). Referring again to the 10%- level of the cdf, we observe a 5 dB difference between class-3 and class-2 clusters, as well as between class-2 and class-1 clusters. The conclusion is that street guidance seems to preserve the polarization more than the propagation over the rooftop, even after a far reflection.

TABLE IV  
AVERAGED CLASS POWERS OF RX 1, RX 2, AND RX 3

RX	Class	hor. Power % of Total Power	vert. Power % of Total Power
1	1	96.5%	95.7%
	2	2.4%	3.8%
	3	1.1%	0.4%
2	1	93.5%	97.2%
	2	4.0%	2.7%
	3	2.5%	0.1%
3	1	46.7%	78.0%
	2	37.2%	12.8%
	3	16.0%	9.2%

#### D. Relative Class Powers

To estimate the significance of different propagation mechanisms that underlie the measurements, we calculate the relative power sum that occurs in the clusters of the three different classes defined in Section III-C. This power was related separately for each TX-position to the associated total power. We distinguished between the three BS sites and the two polarizations, to compare the different environments. Table IV lists the relative class powers for each RX-site and polarization. At RX 1 and RX 2 (below and at the rooftop), only class 1 clusters play a significant role (street guided propagation) with 93% to 97% of the total received power. Class 2 and class 3 (over the rooftop propagation) is negligible. Especially the broad Kaisaniemenkatu street directly in front of RX 2 dominates its environment by over 97% for the more important copolarized component.

The antenna array at site RX 3 shows a different behavior. Here, the classes 2 and 3 in general become more important. The relative contribution of class 3 is 25–100 times stronger at RX 3 than at RX 1 and RX 2. This is due to a large cathedral that acts as a major far reflector for the RX 3 site. The relative power of horizontally (cross-) polarized waves VP-HP is significantly higher than for vertical (co) polarized VP-VP, in clusters of classes 2 and 3. Note that this behavior is true only for the relative power. The absolute power of the vertical component of the classes 2 and 3 is still 5–7 dB higher than that of the horizontal components.

#### E. CDF of the Number of Clusters

We now explore the distribution of the number of clusters, i.e., we investigate how many clusters are seen by the BS. Remember that we transmit from the MS only vertically polarized.

Fig. 19 shows the cumulative distribution function of the number of clusters that are seen by the BS for all available RX- and TX-positions. The total number of clusters that we identified was 273. Separately for the three classes 1–3, we identified 119, 48, and 106 different clusters, respectively. In no case there are less than two clusters, the most probable number of clusters is three. On average, the BS has to handle 3.8 clusters and the upper bound is eight clusters. Note that the maximum number of clusters depends on the classification we made by visual inspection of the results (see Section III-C)—there are always some weak waves left that are hard to assign to clusters. The difference of the power captured by the clusters to the total received power—that can be calculated, e.g., by means of the

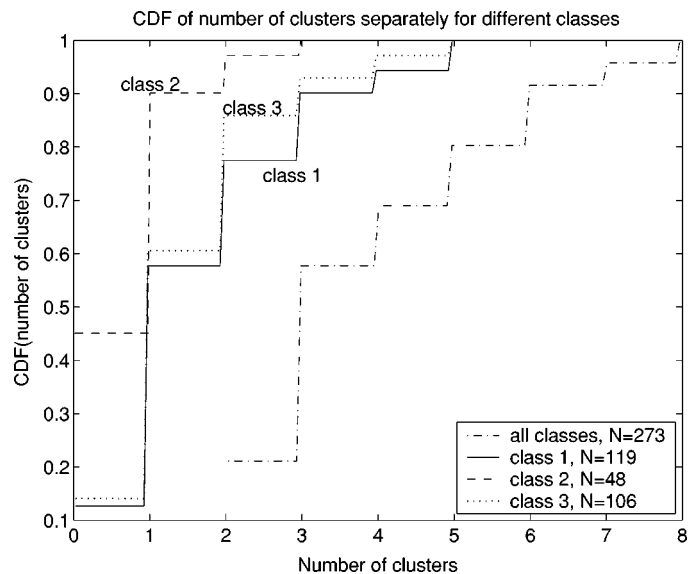


Fig. 19. CDF of the number of clusters; total number of clusters  $N = 273$ . All clusters regardless of the class and separately for the three classes.  $N$  is the number of clusters in a particular class.

spatial integral over the whole angular range—was less than 1.5 dB.

Additionally, the cdfs are shown separately for the three classes. The behavior for street guidance and far-reflection (classes 1 and 3) is similar to the global behavior. But clusters of over-the-rooftop direct propagation are rare. In 90% of the cases, there is only one or even no clusters at all present in class 2.

## V. SUMMARY AND CONCLUSION

We report statistical evaluations of directionally resolved impulse responses measured at 80 different TX positions and three different RX (BS) sites. The impinging energy is concentrated in clusters that are distinct in the azimuth-, elevation-, or delay-domains. Clusters, which are well identifiable in connection with the city map, group together several individual waves that are separable by super-resolution methods. The environment of the BS has more influence on the location of the clusters, especially in the azimuth-elevation plane, than the exact position of the MS.

The cluster powers decrease exponentially with increasing delay by about 8.9 dB/ $\mu$ s. Their standard deviation from this exponential law is independent of the delay, its value is 9.0 dB. While the average relative power of the strongest cluster is 83% of the total power, it is only 41% for the quasi-LOS components, which arrive first at the receiver.

We also investigate how many clusters are required to collect the main part of the total received power. The cdf of the relative power shows that in 90% of all cases we get at least 55% of the copolarized component within the strongest cluster and 75% within the two strongest clusters. From this we can conclude that pointing only a single beam—whose beam width has to be adapted to the extent of the corresponding cluster—from the BS toward the strongest cluster, we will lose 2.6 dB of the total available power and only 1 dB when pointing two beams to the two strongest clusters. Using more than two clusters hardly increases the received power.

Later clusters have in general a higher XPD than shorter delayed ones, on average over all clusters the XPD is 8 dB. An interesting behavior is that reflections from higher locations (elevation  $> 0^\circ$ ) tend to have lower XPD.

We observe that street-guided propagation dominates the received power, as long as the BS is below or at the rooftop level. In that case the relative importance of these clusters is at least 90% of the received energy. If the BS is higher than the rooftop-level of the surrounding buildings, the relative importance of over-the-rooftop components increase from less than 5% to 10%–40% (depending on the polarization). Reflections from far, high buildings become stronger if these buildings have a LOS connection to the receiver. Nevertheless, the street-guided propagation always dominates.

In 90% of the cases, there are at most six clusters seen by the BS, whereas the most probable number of clusters is three. The importance of class-2 clusters (direct over the rooftop) is significantly lower than for other propagation mechanisms. Both the number of such clusters and their relative power are almost negligible.

In general, we conclude that due to the limited number of clusters and the concentration of the received power in the two strongest clusters, an adaptive antenna BS equipped with four to six antennas is able to collect most of the mobile's power up to a loss of about 1 dB. Our XPD-investigations show that polarization diversity will not lead to an increased diversity order as long as the TX polarization is vertical.

#### APPENDIX

##### LEAST-SQUARES ESTIMATOR OF PROPAGATION COEFFICIENTS

The vector  $\vec{P}$  contains the powers of the clusters, the vector  $\vec{\tau}$  denotes the corresponding mean delays. A particular cluster  $i$  has mean delay is  $\tau_i$ , its power is  $P_i$ . Note that the power is given linear, not in dB. We model the relation between the delays  $\vec{\tau}$  and the powers  $\vec{P}$  as exponential

$$P_n \propto P(\tau_n) = ae^{-\tau_n/b}. \quad (1)$$

The parameter  $b$  denotes the the power decrease of the clusters per delay unit, and  $a$  shifts the whole exponential function up or down. That is,  $a$  corresponds to the average attenuation of all clusters that have a delay of 0 ns. We collect  $a$  and  $b$  into the parameter vector  $\vec{\theta}$ ,

$$\vec{\theta} = \begin{pmatrix} b \\ a \end{pmatrix}$$

and separate the estimation problem into a nonlinear problem for  $b$  and a linear problem for  $a$ . The estimated signal becomes

$$\vec{s}(\vec{\theta}) = \mathbf{H}(b) \cdot a \quad (2)$$

where

$$\mathbf{H}(b) = e^{-\vec{\tau}/b}. \quad (3)$$

In our particular case  $\mathbf{H}$  reduces to a  $N \times 1$  matrix. The least squares estimator for  $\vec{\theta}$  reads as follows:

- 1)  $b$  fix:  $\hat{a}_{LS} = \hat{a}_{LS}(b) = (\mathbf{H}^T \mathbf{H})^{-1} \mathbf{H}^T \vec{P}$
- 2)  $\hat{b}_{LS} = \operatorname{argmax}_b \{ \vec{P}^T \mathbf{H} (\mathbf{H}^T \mathbf{H})^{-1} \mathbf{H}^T \vec{P} \}$

Having  $\hat{b}_{LS}$ , we are able to calculate  $\hat{a}_{LS} = \hat{a}_{LS}(b)$ . The nonlinear operator  $\mathbf{H}$  usually does not allow a closed-form expression of  $\hat{b}_{LS}$ , but as it is a one-dimensional parameter-vector, a grid search is easily implemented.

We define the logarithmic estimation error  $\vec{v}$  as

$$\vec{v} = 10 \log \vec{P} - 10 \log \vec{s}(\vec{\theta}) \quad (4)$$

and its standard deviation  $\sigma_v$  as

$$\sigma_v = \sqrt{\operatorname{var}\{\vec{v}\}} \quad (5)$$

because then it is the standard deviation of the underlying log-normally distributed fading process.

#### REFERENCES

- [1] A. Paulraj and C. Papadias, "Space-time processing for wireless communications," *IEEE Signal Processing Mag.*, vol. 14, pp. 49–83, Nov. 1997.
- [2] S. C. Swales, M. Beach, D. Edwards, and J. P. McGeehan, "The performance enhancement of multibeam adaptive base-station antennas for cellular land mobile radio systems," *IEEE Trans. Veh. Technol.*, vol. 39, pp. 56–67, Feb. 1990.
- [3] F. Adachi, M. Sawahashi, and H. Suda, "W-CDMA: Performance evaluation and future enhancement," in *Proc. Eur. Personal Mobile Communications Conf. (EPMCC'99)*, Paris, 1999, pp. 429–434.
- [4] J. C. Liberti and T. S. Rappaport, *Smart Antennas for Wireless Communications*. Englewood Cliffs, NJ: Prentice-Hall, 1999.
- [5] R. B. Ertel, P. Cardieri, K. W. Sowerby, T. S. Rappaport, and J. H. Reed, "Overview of spatial channel models for antenna array communications systems," *IEEE Personal Commun.*, vol. 5, no. 1, pp. 10–22, Feb. 1998.
- [6] M. Steinbauer and A. F. Molisch, *Spatial Channel Modeling*, L. H. Correia, Ed., Wiley, 2001. *Wireless Flexible Personalized Communications—COST 259: European Cooperation in Mobile Radio Research*, submitted for publication.
- [7] U. Martin, J. Fuhl, I. Gaspard, M. Haardt, A. Kuchar, C. Math, A. F. Molisch, and R. Thomä, "Model scenarios for direction-selective adaptive antennas in cellular mobile communication systems—Scanning the literature," *Wireless Personal Commun. Mag.*, (Special Issue on Space Division Multiple Access), vol. 11, no. 1, pp. 109–129, Oct. 1999.
- [8] K. Pedersen, P. Mogensen, and B. Fleury, "A stochastic model of the temporal and azimuthal dispersion seen at the base station in outdoor propagation environments," *IEEE Trans. Veh. Technol.*, vol. 49, no. 2, pp. 437–447, Mar. 2000.
- [9] J. Fuhl, J.-P. Rossi, and E. Bonek, "High resolution 3-D direction-of-arrival determination for urban mobile radio," *IEEE Trans. Antennas Propagat.*, vol. 4, pp. 672–682, 1997.
- [10] A. Kuchar, J.-P. Rossi, and E. Bonek, "Directional macro-cell channel characterization from urban measurements," *IEEE Trans. Antennas Propagat.*, vol. 48, pp. 137–146, Feb. 2000.
- [11] K. Kalliola, H. Laitinen, L. Vaskelainen, and P. Vainikainen, "Real-time 3D spatial-temporal dual-polarized measurement of wideband radio channel at mobile station," *IEEE Trans. Instrum. Meas.*, vol. 49, pp. 439–448, Apr. 2000.
- [12] J. Laurila, K. Kalliola, M. Toeltsch, K. Hugel, P. Vainikainen, and E. Bonek, "Wideband 3-D characterization of mobile radio channels in urban environment, in *IEEE Trans. Antennas and Propagation*, submitted for publication.
- [13] K. Kalliola, J. Laurila, M. Toeltsch, K. Hugel, P. Vainikainen, and E. Bonek, "3-D directional wideband dual-polarized measurement of urban mobile radio channel with synthetic aperture technique," presented at the Millennium Conference on Antennas and Propagation (AP2000), Davos, Switzerland, Apr. 2000.
- [14] J. Kivinen, T. Korhonen, P. Aikio, R. Gruber, P. Vainikainen, and S.-G. Häggman, "Wideband radio channel measurement system at 2 GHz," *IEEE Trans. Instrum. Meas.*, vol. 48, pp. 39–44, Feb. 1999.
- [15] K. Kalliola and P. Vainikainen, "Characterization system for radio channel of adaptive array antennas," in *Proc. Int. Symp. Personal Indoor Mobile Radio Conf. (PIMRC'97)*, Helsinki, Finland, 1997, pp. 95–99.
- [16] R. Roy, A. Paulraj, and T. Kailath, "ESPRIT—A subspace rotation approach to estimation of parameters of cisoids in noise," *IEEE Trans. Acoust., Speech, Signal Processing*, vol. 32, pp. 1340–1342, May 1986.

- [17] M. Zoltowski, M. Haardt, and C. Mathews, "Closed-form 2-D angle estimation with rectangular arrays in element space or beamspace via unitary ESPRIT," *IEEE Trans. Signal Processing*, vol. 44, pp. 316–328, Dec. 1994.
- [18] M. Haardt and J. Nosske, "Unitary ESPRIT: How to obtain an increased estimation accuracy with a reduced computational burden," *IEEE Trans. Signal Processing*, vol. 43, pp. 1232–1242, May 1995.
- [19] H. Krim and M. Viberg, "Two decades of array signal processing research," *IEEE Signal Processing Mag. (Special Issue on Array Processing)*, vol. 13, July 1996.
- [20] M. Steinbauer, D. Hampicke, G. Sommerkorn, A. Schneider, A. F. Molisch, R. Thomä, and E. Bonek, "Array-measurement of the double-directional mobile radio channel," presented at the IEEE Vehicular Technology Conference (VTC 2000-Spring), Tokyo, May 2000.
- [21] L. H. Correia, *Wireless Flexible Personalized Communications—COST 259: European Co-operation in Mobile Radio Research*, L. H. Correia, Ed. NY: Wiley, Mar. 2001, p. 512.
- [22] *Digital Land Mobile Radio Communications—COST 207*, 1989. Commission of the European Communities.



**Martin Toeltsch** (S'00) received the Dipl.-Ing. degree (M.S.) in communications engineering (highest honors) from the Technische Universität Wien (TU-Wien), Vienna, Austria, in 1998. He is currently working toward the Ph.D. degree.

From 1992 to 1998, he worked in the field of signal and image processing for medical applications. His research now focuses on OFDM and radio channel measurements, as well as propagation and channel modeling.

Mr. Toeltsch has been a member of the Mobile Communications Group at the Institut für Nachrichten- und Hochfrequenztechnik (INTHF), TU-Wien, Vienna, Austria.



**Juha Laurila** (S'97–M'00) was born in Korpilahti, Finland, in 1970. He received the M.Sc. (E.E.) degree from the Helsinki University of Technology, (Institute of Radio Communications), Helsinki, Finland, in 1995 and the Dr.Tech. degree from the Vienna University of Technology (Institut fuer Nachrichtentechnik und Hochfrequenztechnik), Vienna, Austria, in 2000.

In his doctoral thesis he investigated semi-blind algorithms for mobile communications concentrating on the reception with multiple antennas at the base station. From 1995 to 1996, he was with the Helsinki University of Technology, and from 1996 to 2000 he was with Vienna University of Technology, Vienna, Austria, working as a Research Engineer at both universities. Since 2000, he has been working as a Senior Research Engineer at Nokia Research Center (Radio Communications Laboratory) Helsinki, Finland. His current research activities are related to the utilization of multiple antenna techniques in cellular systems. His main interests are in link-level algorithm development, but he is also involved with spatial propagation studies and smart antenna system-level investigations. He has authored or coauthored more than 20 international reviewed journal and conference publications.



**Kimmo Kalliola** was born in Helsinki, Finland, in 1972. He received the degrees of Master of Science in technology and Licentiate of Science in technology from Helsinki University of Technology (HUT), Helsinki, Finland, in 1997 and 2000, respectively.

From 1997 to 2001, he worked as a Research Engineer at the Radio Laboratory of HUT, where he is currently pursuing the degree of Doctor of Science in Technology. Since 1999, he has been also with the Radio Communications Laboratory of Nokia

Research Center, Helsinki, Finland. His research interests are in spatial radio channel measurements and modeling.



**Andreas F. Molisch** (S'89–M'95–SM'00) received the Dipl. Ing., Dr. Techn., and the habilitation degrees from the Technical University, Vienna, Austria, in 1990, 1994, and 1999, respectively.

From 1991 to 2001, he was with the Institut fuer Nachrichtentechnik und Hochfrequenztechnik (INTHFT) of the TU Vienna, Vienna, Austria, becoming an Associate Professor, in 1999. From 1999 to 2000, he was on leave to the FTW Research Center for Telecommunications, Vienna. Since March 2001, he has been with the Wireless Systems Research Department at AT&T Laboratories—Research in Middletown, NJ. He has done research in the areas of surface acoustic wave filters, radiative transfer in atomic vapors, atomic line filters, and BS antennas. His current research interests are the measurement and modeling of mobile radio channels, MIMO systems, smart antennas, and wideband wireless systems. He has authored, coauthored or edited two books, five book chapters, some 45 journal papers, and numerous conference contributions.

Dr. Molisch is an editor of the IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, and coeditor of an upcoming special issue in the IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS ON MIMO and Smart Antennas in *J. Wireless Comm. Mob. Comp.* He has participated in the European research initiatives "COST 231," "COST 259," and "COST 273." He has also been Session Organizer, Session Chairman, and Member of the Program Committee of various international conferences. He is a member of OeVE and VDE. He received the GiT prize, in 1991, the Kardinal Innitzer prize, in 1999, and an INGVAR award, in 2001.



**Pertti Vainikainen** (M'91) was born in Helsinki, Finland, in 1957. He received the degree of Master of Science in technology, Licentiate of Science in technology and the Doctor of Science in technology from Helsinki University of Technology (HUT), Helsinki, Finland, in 1982, 1989, and 1991, respectively.

From 1981 to 1992, he worked at the Radio Laboratory of HUT mainly as a Teaching Assistant and Researcher. From 1992 to 1993, he was Acting Professor of Radio Engineering, since 1993, Associate Professor of Radio Engineering, and since 1998, Professor in Radio Engineering, all at the Radio Laboratory of HUT. In 1993–97 he was the director of the Institute of Radio Communications (IRC) of HUT. His main fields of interest are antennas and propagation in radio communications and industrial measurement applications of radio waves. He is the author or coauthor of 3 books and over 110 refereed international journal or conference publications and the holder of four patents.



**Ernst Bonek** (M'73–SM'85) was born in Vienna, Austria, in 1942. He received the Dipl. Ing. and Dr. Techn. degrees (highest honors) from the Technische Universität Wien (TU Wien), Vienna, Austria.

In 1984, he was appointed Full Professor of Radio Frequency Engineering at the TU Wien. His field of interest is in mobile communications at large. Recent contributions concern smart antennas, the characterization of mobile radio channels, and advanced antennas and receiver designs. Altogether, he authored or coauthored some 150 journal and conference publications. He holds several patents on mobile radio technology.

Dr. Bonek served the IEEE Austria Section as a Chairman, from 1985 to 1990. From 1991 to 1994, he was a Council Member of the Austrian Science Fund, acting as Speaker for Engineering Sciences. From 1996 to 1999, he served on the Board of Directors of the reorganized Post and Telekom Austria. He participated in the European research initiative COST 259 as Chairman of the working group on Antennas and Propagation, and continues to serve in this position in COST 273. In URSI, he is presently chairman of Commission C "Signals and Systems." He is an Area Editor of "Wireless Personal Communications."