Correspondence

The Performance of Polarization Diversity Schemes at a Base Station in Small/Micro Cells at 1800 MHz

Jukka J. A. Lempiäinen and Jaana K. Laiho-Steffens

***Abstract*—The aim of this paper is to evaluate experimentally the relationships between cross-polarization discrimination (XPD), signal cross correlation, and polarization diversity gain with horizontally/vertically (HV) polarized reception at the base-station (BS) end at 1800 MHz. The performance of the horizontal/vertical polarization diversity scheme was also compared with a diversity scheme with ±45° slanted polarizations and horizontal space diversity at 1800 MHz in a personal communication system (PCS) mobile network. A measurement campaign was conducted in small/micro cells in different types of areas, taking into account the influence of mobile antenna inclination. According to the measurements, XPD values for horizontal/vertical polarizations vary between 5–15 dB, depending on the environment. Furthermore, XPD values depend highly on the radio propagation path between the BS and mobile station (MS) due to line-of-sight (LOS) and nonline-of-sight (NLOS) situations. Signal cross correlations of horizontal and vertical polarizations in both LOS and NLOS situations were clearly below 0.7, which is the generally accepted value to have a reasonable improvement at the receiving end with diversity. Finally, the results showed that almost equal diversity gain and system performance in a PCS network at 1800 MHz can be achieved in small/micro cells in different environments with ±45° slanted polarizations at the BS end when comparing results with horizontal space diversity. The performance of horizontal/vertical polarization diversity scheme was approximately 1 dB worse than horizontal space diversity.**

***Index Terms*—Cross-polarization discrimination, polarization diversity, signal correlation.**

I. Introduction

Multipath propagation causes Rayleigh fading in nonline-of-sight (NLOS) and Rician fading in line-of-sight (LOS) paths in a radio propagation channel [1]. Horizontal space diversity is traditionally used to reduce fading problems at the base-station (BS) end in mobile networks. However, two separate receiving antennas are required when this scheme is applied and antenna implementation is spatially large. In mobile networks, high-capacity requirements in urban areas force operators to use small/micro cells. In an urban environment, space for BS antennas is usually limited because of wall implementations. Polarization diversity is one of the most promising techniques to reduce fading with a compact antenna configuration requiring only one antenna location. The applicability of polarization diversity can partly be evaluated analyzing signal cross correlation and cross-polarization discrimination (XPD) values. Signal cross correlations of different antenna configurations including horizontal and vertical polarizations have been studied in small and micro cells in [2]. XPD of horizontal and vertical polarization has been evaluated in different types of areas in [3]–[5]. The ±45° slanted polarization diversity has also been studied in [6], but is not related to different environments. Thus, a complete study, where signal cross correlation, XPD, and finally diversity gain of horizontal/vertical polarization diversity schemes are compared with each other in different types of areas, especially in a microcellular environment, is needed. Additionally, a comparison of the performance of space diversity and different polarization diversity schemes supports a selection of diversity techniques for different environments.

The first aim of this paper is to clarify the influence of an environment on polarization diversity scheme in small/micro cells. This is based on the evaluation of two parameters: XPD and signal cross correlation. The second target is to study the system performance of two different polarization diversity schemes (horizontal/vertical and ±45° slanted polarizations) and compare them with horizontal space diversity in different environments. The system performance is related to measured quality values on certain received field-strength levels. Moreover, the diversity gain is here defined as the system performance improvement when comparing nondiversity and diversity receptions. Special attention is paid to the microcellular environment because of the increased need for small cells in mobile networks. Thus, the main objective of this study is to understand the performance of polarization diversity in small/micro cells because there are usually several LOS paths in these environments. In an LOS path, diversity gain itself may disappear if one polarization dominates while the signal mean level difference of individual polarizations is excessive. Hence, mobile antenna inclination has an effect on diversity gain in LOS path. The superior diversity gain can be obtained when received signal mean levels of individual polarizations are approximately at an equal level. This happens usually in an NLOS path if there are enough reflecting surfaces between MS's and BS's. In small/micro cells, the number of reflections in a radio propagation path is limited because the small cell radius and performance of polarization diversity schemes have to be clarified also in the NLOS path. The superior system performance of different polarization diversity schemes in LOS and NLOS situations is related to signal mean level differences, and it is evaluated in this study in different environments taking into account mobile antenna inclination.

II. Measurement Configurations and Environment

The first objective of the measurement campaign was to study the relationship between XPD, signal cross correlation, and gain of horizontal/vertical polarization diversity schemes. Particular attention was paid to results in a microcellular environment where all the above-mentioned parameters were evaluated. First, XPD measurements of horizontal/vertical polarizations were conducted in different types of areas to show the influence of the environment on the performance of a polarization diversity scheme. Second, a semiurban microcellular environment was selected, and signal cross correlations were measured having polarizations, location of receiving antennas, and measurement routes consistent with XPD measurements. In this semiurban microcellular environment, both LOS and NLOS paths were analyzed separately. Next, polarization diversity gain was evaluated in small/micro cells in different types of areas using horizontal/vertical or ±45° slanted polarizations at the reception. Finally, space diversity measurements with 20λ horizontal separation were performed, and these results were compared with the performance of both polarization diversity schemes. The separation of receiving antennas was 20λ in the space diversity scheme in

Manuscript received March 28, 1997; revised August 19, 1997.

The authors are with Nokia Telecommunications, FIN-00045 Nokia Group, Finland.

Publisher Item Identifier S 0018-9545(98)05669-2.

0018–9545/98$10.00 © 1998 IEEE

order to achieve low-signal cross correlations and, thus, superior space diversity gain that can be compared with polarization diversity gains.

A. Environments

The length of a radio propagation path between an MS and BS was always less than 1.0 km throughout the measurement campaign. Thus, measurements were conducted using small/micro cells at each BS site. XPD measurements were performed at two BS sites. One of the sites was the Nokia office building in Leppävaara, and the other one was the water tower in Otaniemi, both in Espoo, Finland. The height of the Leppävaara site was 15 m. Most of the surrounding buildings at the Leppävaara site were higher than the site itself. Leppävaara could be classified between semiurban and suburban areas, and part of the measurements were performed in a microcellular environment while receiving antennas were clearly below the average rooftop level of surrounding buildings. One direction of the Leppävaara site could be considered as a light suburban type having only a few houses in that area. The height of the Otaniemi water tower was some 40 m, which was slightly higher than the sites normally. The tower was standing on a hill, and the terrain height difference between the site and some of the mobile locations caused the total height of the site to be even more. In Otaniemi, the measured areas were the university campus, which could be classified as a mixture of open and suburban, and Tapiola, which is more "dense suburban" than urban. Several routes were driven at both BS site locations to cover as many different area types as possible. Signal cross correlations were measured only at the Leppävaara site in a semiurban microcellular environment because the relation between XPD and signal cross-correlation values, especially in LOS and NLOS situations in this type of area, was of interest. System measurements for diversity gain were performed at Leppävaara, Mäkkylä, and Kilo sites including different types of environments—urban, semiurban, light suburban, and indoor. At the Leppävaara site, diversity gain was measured in the direction of semiurban microcellular environments along the same route that was used in XPD and signal cross-correlation measurements. Additionally, indoor measurements were performed inside the Nokia office while receiving antennas were installed on the rooftop of the same building. The measurement environment at the Mäkkylä site represents a light suburban-area type. Receiving antennas were installed on the rooftop of the site (antenna height of 20 m), and there were few one–two-floor houses in a measurement area. At the Kilo site, receiving antennas were installed on the rooftop of the office building at the height of 25 m. The surroundings of the Kilo site represent a typical urban environment having several four–seven-floor office buildings in a propagation path between a mobile station (MS) and BS.

B. Equipment

In XPD and signal cross-correlation measurements, two Rohde–Schwarz test receivers were used at the BS end. Test receivers were synchronized and triggered externally by pulse generator. A network measurement system (NMS/X) controlled the whole measurement setup recording data and storing it to the files. The sampling rate was 80 Hz, and the transmitter was moving approximately 3 km/h in order to have enough samples over the wavelength to show Rayleigh fading. Thus, results have a good correspondence on slow-moving mobiles which are interfered mostly by Rayleigh fading. A dual-polarized receiving antenna (horizontal and vertical polarizations with 28-dB decoupling) was implemented on the rooftop of the sites. Both receiving end chains were calibrated before the measurements to indicate power difference due to cables and connectors. A signal generator was transmitting in a continuous-wave mode power of 1.0 W. A transmitting antenna was a dipole with vertical linear polarization (antenna inclination 0° from the vertical plane) and with 20 dB or better decoupling between vertical and horizontal polarizations.

Diversity gain measurements were made in a DCS1800 cellular network based on a global system for mobile communication (GSM) standard and having a radio infrastructure—BS controllers (BSC's) and BS—manufactured by Nokia Telecommunications. A GSM protocol analyzer (GPA) for the DCS1800 network was gathering data reported by the BS to the BSC and storing it to the files. Thus, measurements at the receiving end were performed after signal combining, which was based on modified maximal ratio combining algorithm and made by the BS in the uplink direction. In these measurements, both dual-polarized BS receiving antennas (horizontal/vertical, $\pm 45^\circ$ slanted) and vertically polarized horizontal space diversity were used. Additionally, only test mobiles were in the network, and, thus, mobile antenna inclination was able to be controlled. Mobile antennas were in the vertical position in measurements when horizontal space diversity was used or diversity was not applied at all. Polarization diversity measurements in different environments were performed with both mobile antenna inclinations 0° and 45° from the vertical plane. Hence, all diversity gain results were based on system measurements while full-rate mobile telephone calls were made in different types of areas in the DCS1800 network.

III. Data Analysis

A short description of the methods used in the data postprocessing and analysis is included in this section. Measurements performed by NMS/X were without any averaging, and the ESVD used a high sampling rate compared with mobile speed. Hence, a moderate mobile speed which caused that recorded signal contained fast fading, which was required when signal cross correlations were measured. However, the fast fading was cancelled for the XPD evaluation, and this was performed using the averaging method of Lee [7]. The short-term fading was cancelled using an average window of 10–20 λ to be able to better visualize long term changes. Finally, XPD values were averaged over the whole measurement route. This double averaging did not bring any changes to the final XPD estimate. Signal cross correletions were also calculated over a certain window to avoid the influence of long-term fading. First, signal cross-correlation values were calculated with a window of 500 samples corresponding approximately 10λ distance in order to see the local values of signal correlations in LOS and NLOS situations. Finally, an average over the whole measurement route, based on preprocessed values, was calculated.

Diversity gain was evaluated based on system measurement results gathered by GPA. Each measurement result contained a pair of samples—received signal strength indicator (RSSI) and quality class—which were measured in the uplink direction after combining the signals received by individual branches in the BS. In diversity gain measurements, received field-strength levels were close to the noise level in order to deteriorate the quality without interference. Quality class is related to bit-error rate (BER): the best and worst classes are zero and seven corresponding BER values $< 0.2\%$ and $> 12.8\%$, respectively. Quality classes were used in data analysis because handovers and power controls due to bad quality are based on quality classes in DCS networks. Each diversity gain measurement contained a minimum of 5000 results (a pair of RSSI and quality values) from each different area type thus having adequate statistical accuracy. Measurement results were processed and probability functions were calculated. Hence, diversity gains were measured over the cell coverage area that represents the particular area type.

TABLE I
MEASURED XPD VALUES IN SMALL CELLS IN DIFFERENT TYPES OF AREAS

AREA DESCRIPTION	MEASURED MEAN XPD VALUES	STANDARD DEVIATION
• suburban area, behind two story building, completely NLOS location	7.5 dB	3 dB
• "semi"urban area, relatively high buildings, light business area, completely NLOS	5.8 dB	5.4 dB
• relatively open area, a few block of flats, part of the route driven is NLOS and part LOS	9.7 dB	3.2 dB
• pure LOS connection	14 dB	4.8 dB
• typical suburban area, not very high building density, NLOS	6.8 dB	4.1 dB

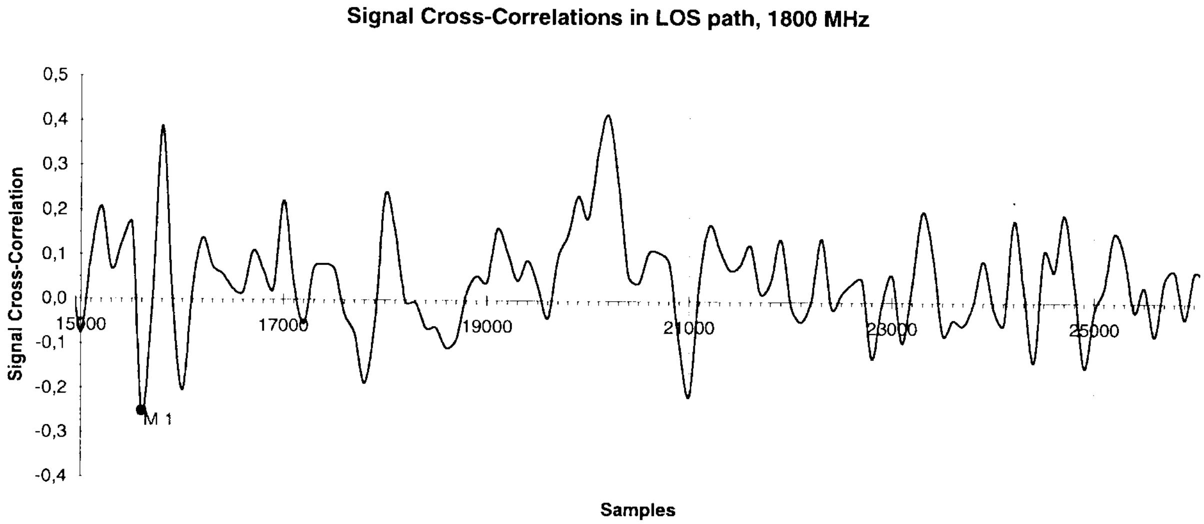

Fig. 1. Signal cross correlations in LOS path in a microcellular environment at 1800 MHz, with receiving antenna implemented on the rooftop.

IV. RESULTS

A. Cross-Polarization Discriminations

One measure of applicability of polarization diversity in different environments is XPD. XPD in this context is specified as a signal mean level difference between two orthogonally polarized signal components—horizontal and vertical. The environment has a great influence on the measured XPD value, and, thus, the area-type description is included together with each result. It is also important to notice that results are related to small/micro cells because the maximum achievable cell radius was less than 1.0 km. A higher radius could provide lower XPD values because of having more reflecting obstacles between BS's and MS's. Mobile antenna inclination was vertical in all XPD measurements. In Table I, typical XPD values and related area descriptions were collected when receiving antennas were installed above the average rooftop level. The values presented in Table I are averaged results of the whole measurement file. Only in open areas, where the LOS situation was dominant, the measured XPD (14 dB) was higher than 10 dB. XPD results were also consistently higher in measurements which were conducted in area types where some LOS situations occurred. For typical suburban areas, the measured XPD values were around 7 dB. The smallest measured XPD was 5.8 dB in a semiurban area. These results give an indication of what XPD could be in a dense urban environment. The more scatterers there are, the better the situation seems to be for a polarization diversity scheme. The XPD values measured in a semiurban microcellular area at the Leppävaara site are given in Table II. These results were consistent with values in Table I related to the same area type having several reflections. XPD was also higher in LOS situations in a microcellular environment even if there were more reflections from the walls of the buildings.

B. Signal Cross Correlations

Signal cross correlations were measured in a semiurban microcellular environment at the Leppävaara site using horizontal and vertical polarizations at the reception. The results were analyzed separately for LOS and NLOS situations in order to show whether low correlations could be achieved in both situations that are common in a microcellular environment. Signal cross correlations in LOS and NLOS situations are illustrated in Figs. 1 and 2 when a receiving antenna was implemented on the rooftop of the office building. Markers (M1, M2, and M3) refer to different locations over the measurement route. LOS situations occur after marker M1 (Fig. 1) and the rest of the route can be considered NLOS path (Fig. 2). The location after marker M3 is the furthest away from the BS. Thus, there are the greatest number of the reflections from the buildings at this location. It is shown in Figs. 1 and 2 that there is no considerable difference in results between LOS and NLOS paths. Additionally, it can be seen that average signal cross correlation over the whole measurement route is clearly less than 0.2. Thus, remarkable diversity gain could be obtained in LOS and NLOS paths in a microcellular environment because signal correlations were $\ll 0.7$, which can be used as a reference in GSM-related systems when frequency hopping (FH) is not applied [8]. Finally, comparing signal cross correlation

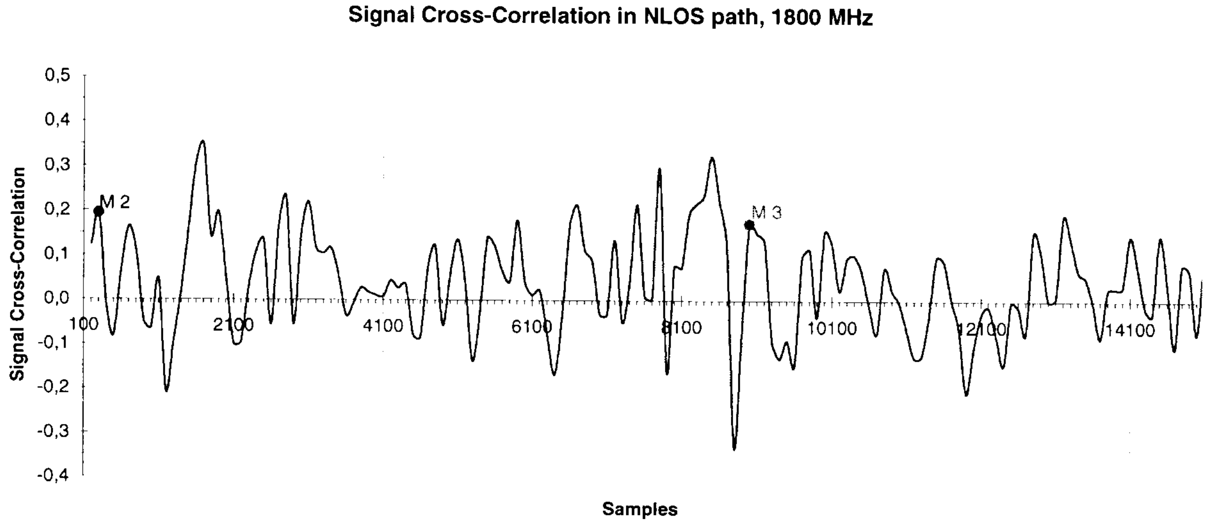

Fig. 2. Signal cross correlations in NLOS path in a microcellular environment at 1800 MHz, with receiving antenna implemented on the rooftop.

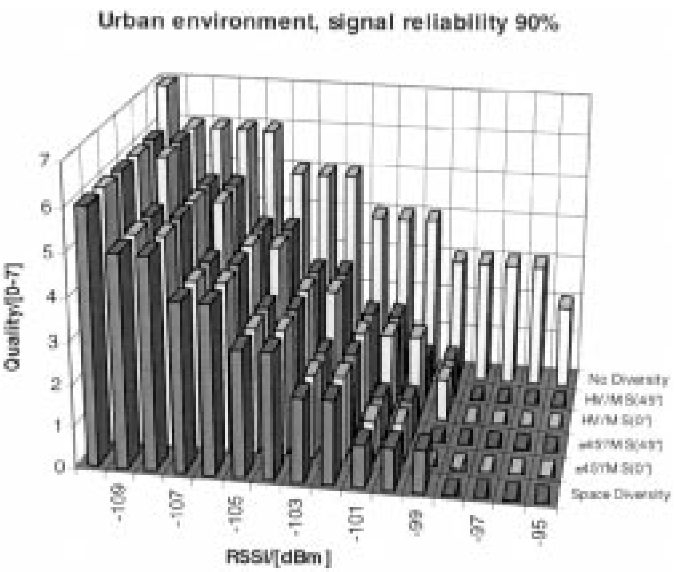

Fig. 3. Received field-strength level and quality distributions in urban area with signal reliability of 90%.

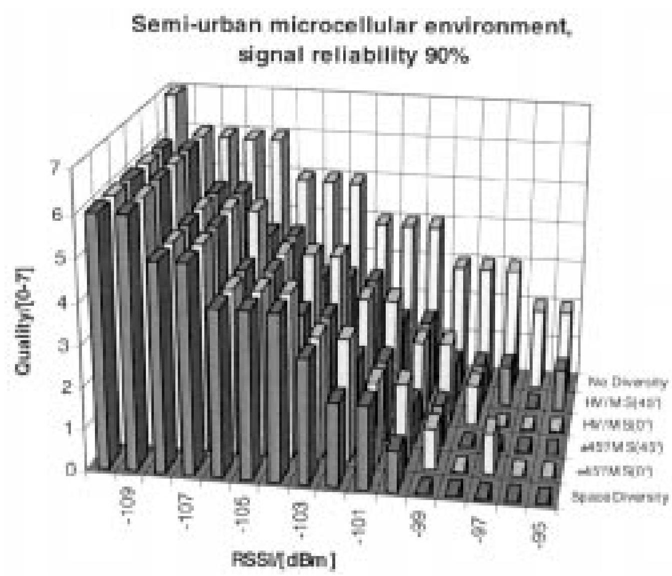

Fig. 4. Received field-strength level and quality distributions in a semiurban microcellular environment with signal reliability of 90%.

and XPD results (Tables I and II and Figs. 1 and 2), it can be noted that XPD is more area-type dependent than signal cross-correlation values. Thus, the influence of XPD on the polarization diversity gain is higher than the influence of signal cross-correlation values.

C. Diversity Gain

Polarization diversity gain was evaluated and compared with that of horizontal space diversity in four different types of areas using horizontal/vertical or $\pm 45^\circ$ slanted polarizations at the receiving end. Received field-strength levels and quality distributions with 90% signal reliability are illustrated in Figs. 3–6 for urban, semiurban microcellular, light suburban, and indoor environments, respectively. In Figs. 3–6, HV and $\pm 45^\circ$ refer to horizontal/vertical and $\pm 45^\circ$ slanted polarization diversity schemes. Correspondingly, MS (0°) and MS (45°) indicate antenna inclination of the MS during polarization diversity measurements. It can be seen in Figs. 3–6 that approximately 1-dB higher field-strength level is required to achieve a certain quality class while comparing horizontal/vertical polarization diversity to horizontal space diversity. This relationship is almost constant in different types of areas. Diversity gain of horizontal/vertical polarizations, illustrated in Fig. 4, can also be compared with XPD values [maximum 9.7 dB (Table II)], which were also measured for a semiurban microcellular area. It can be noted that horizontal/vertical polarization diversity gain is approximately 1 dB lower than that of horizontal space diversity when signal mean level difference between individual polarizations is up to 10 dB. Results in Figs. 3–6 also show that mobile antenna inclination does not affect diversity gain significantly if there is no LOS connection between the MS and BS. Finally, horizontal/vertical polarization diversity scheme can be compared with the reception with $\pm 45^\circ$ slanted polarizations. Figs. 3–6 show that $\pm 45^\circ$ slanted polarization diversity scheme is better than horizontal/vertical polarizations at the receiving end, and it achieves almost equal performance with horizontal space diversity in different environments with mobile antenna inclination 0° or 45° from the vertical plane. Polarization diversity gains and differences compared with horizontal space diversity in different types of areas

TABLE II
MEASURED XPD VALUES IN A SEMIURBAN MICROCELLULAR ENVIRONMENT

AREA DESCRIPTION	MEASURED MEAN XPD VALUES	STANDARD DEVIATION
• semi-urban microcellular area, one large 20 m high building blocking the propagation path, NLOS	8.4 dB	2.5 dB
• semi-urban microcellular area, some vegetation, 150 m from the site	9.7 dB	4.4 dB
• semi-urban microcellular area, 3 to 4 story buildings blocking the propagation path, building density rather high, route driven is mostly NLOS	6.7 dB	3.5 dB
• semi-urban microcellular area, NLOS, relatively heavy vegetation and building density	7.7 dB	5 dB

TABLE III
POLARIZATION DIVERSITY GAINS IN DIFFERENT ENVIRONMENTS

Area type	Diversity gain with ±45° polarizations, MS(0°) / MS(45°)	Compared with horizontal diversity	Diversity gain with HV polarizations, MS(0°) / MS(45°)	Compared with horizontal diversity
Indoor	6 dB / 6 dB	0 / 0 dB	5 dB / 6 dB	-1 / 0 dB
Urban	6 dB / 6 dB	0 / 0 dB	5 dB / 5 dB	-1 / -1 dB
Semi-urban microcellular	4 dB / 5 dB	0 / +1 dB	3 dB / 5 dB	-1 / +1 dB
Light suburban	3 dB / 3 dB	0 / 0 dB	3 dB / 2 dB	0 / -1 dB

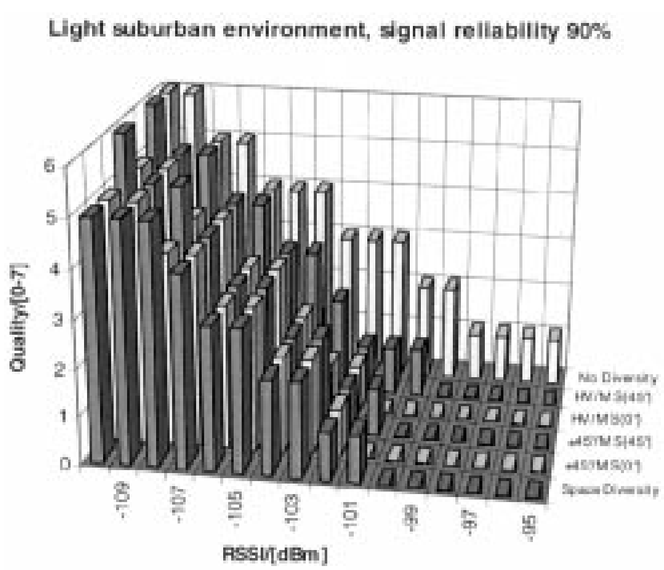

Fig. 5. Received field-strength level and quality distributions in light suburban area with signal reliability of 90%.

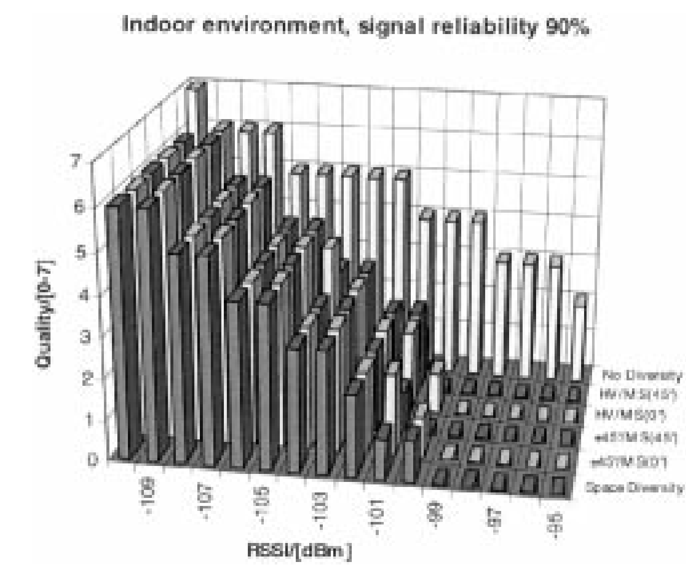

Fig. 6. Received field-strength level and quality distributions in indoor environment with signal reliability of 90%.

are gathered in Table III when quality class 3 is exceeded with 90% signal reliability. When comparing the measured urban results (Table III) with simulated ones [8], it can be noted that system performance is better than simulations predict.

V. CONCLUSIONS

In this paper, the relationship between XPD, signal cross correlation, and diversity gain of a horizontal/vertical polarization scheme in a small/micro cell environment at 1800 MHz was studied. Additionally, diversity gains of horizontal/vertical and $\pm 45^\circ$ slanted polarization diversity schemes were evaluated in different types of areas and compared with that of the horizontal space diversity scheme at 1800 MHz. XPD's were measured in different types of areas, and the results showed that the lowest XPD values could be obtained in the area where there were several scatterers between BS's and MS's. According to the measurements, low XPD values could also be achieved in a microcellular environment in NLOS situations. Low-signal cross-correlation values were also achieved in LOS and NLOS situations in a microcellular environment. Thus, diversity gain of different polarization schemes depends more on signal mean differences between two receiver branches. Horizontal/vertical polarization diversity gain was in different measured locations approximately 1 dB lower than that of horizontal space diversity gain. Moreover, it was noted that the performance of horizontal/vertical polarization diversity gain was almost constant when XPD values were $\leq$ 10 dB. Finally, the horizontal/vertical polarization diversity gain was compared with $\pm 45^\circ$ slanted polarization diversity gain that was almost equal in all measured environments compared with horizontal space diversity. It was also noted that mobile antenna inclination did not have a significant effect on the diversity gain regardless of which polarization diversity scheme was applied.

ACKNOWLEDGMENT

This paper was undertaken using measurement equipment developed by Nokia Telecommunications and the Nokia DCS1800 mobile network. The authors would like to thank all their colleagues for advice throughout the project.

REFERENCES

[1] D. Parsons, *The Mobile Radio Propagation Channel*. London, U.K.: Pentech, 1992.
[2] P. C. F. Eggers, J. Toftgård, and A. M. Oprea, "Antenna systems for base station diversity in urban small and micro cells," *IEEE J. Select. Areas Commun.*, vol. 11, no. 7, pp. 1046–1057, 1993.
[3] R. G. Vaughan, "Polarization diversity in mobile communications," *IEEE Trans. Veh. Technol.*, vol. 39, no. 3, pp. 177–186, 1990.
[4] A. M. D. Turkmani, A. A. Arowojolu, P. A. Jefford, and C. J. Kellett, "An experimental evaluation of the performance of two-branch space and polarization diversity schemes at 1800 MHz," *IEEE Trans. Veh. Technol.*, vol. 44, no. 2, pp. 318–326, 1995.
[5] J.-F. Lemieux, M. S. El-Tanany, and H. M. Hafez, "Experimental evaluation of space/frequency/polarization diversity in the indoor wireless channel," *IEEE Trans. Veh. Technol.*, vol. 40, no. 3, pp. 569–574, 1991.
[6] S. Kozono, T. Tsuruhara, and M. Sakamoto, "Base station polarization diversity reception for mobile radio," *IEEE Trans. Veh. Technol.*, vol. VT-33, no. 4, pp. 301–306, 1984.
[7] W. C. Y. Lee, *Mobile Cellular Telecommunication Systems*. New York: McGraw-Hill, 1990, p. 449.
[8] P. E. Mogensen and J. Wigard, "On antenna and frequency diversity in GSM related systems (GSM-900, DCS-1800 and DCS-1900)," in *Proc. IEEE PIMRC'96*, Taipei, Taiwan, Oct. 1996, pp. 1272–1276.
[9] W. C. Jakes, Jr. (Ed.), *Microwave Mobile Communications*. New York: Wiley–Interscience, 1974.