Signal Correlations and Diversity Gain of Two-Beam Microcell Antenna

Jukka J. A. Lempiäinen and Keijo I. Nikoskinen

Abstract—**The motivation of the present study is to investigate the possibility of using two independently directed antenna beams in a mobile base station to provide diversity gain and reduce fading problems in a microcellular environment. In this paper, the signal correlation of the individual antenna beams is studied, and it is shown that correlation depends on beamwidth, separation angle of the antenna beams, and the location of the base-station antenna array. Signal correlations have been computed using narrow- and wide-beam antennas in two separate base-station antenna locations. Diversity gains of both antenna types have been optimized by selecting the beam orientations which minimize the signal correlation. The numerical simulations show that a considerable diversity gain can be obtained using this approach.**

Index Terms—**Diversity, fading, propagation.**

I. Introduction

THE EFFECT of Rayleigh fading due to multipath propagation in a radio propagation channel in mobile networks such as personal communication systems (PCS's) can be reduced by using different diversity schemes [1]–[5]. Conventionally, space diversity technique, especially horizontal separation of receiving antennas, has been used in mobile networks in urban areas. References [1]–[5] represent recently reported new diversity methods that are not yet used as widely in mobile networks. All these new techniques—polarization, jitter, switched pattern, and beam diversities—have been developed to avoid spatially large antenna configurations and to provide compact base-station antenna implementations in urban microcells. Space diversity gain can also be obtained with only a small separation of receiving antennas, especially in the horizontal direction when antennas are installed clearly below the average rooftop level [6]. However, spatial size of space diversity configuration depends strongly on antenna height. Thus, new diversity schemes have become increasingly interesting because of their superiority compared to space diversity, which is due to need of only one base-station antenna array. The application of directed antenna beams is an attractive alternative to bring about diversity gain since the received signal of a beam depends on its width and orientation. Diversity gain associated with directed beams is also technically a compact solution because it is provided by a single antenna array. Still, the performance of this new diversity technique depends on the environment, especially when microcells are considered. Analyzing a nonline-of-sight (NLOS) path is not enough because line-of-sight (LOS) paths are common as well, and, thus, the optimal antenna-beam direction cannot be deduced definitely due to some dominant signal reflections and diffractions from the buildings and corners in an urban area [7]. Hence, a more detailed study is needed in order to achieve the best benefit of directed antenna beams when diversity gain is required in a Rayleigh propagation channel (NLOS path) and in a Rician propagation channel (LOS path) at the same time.

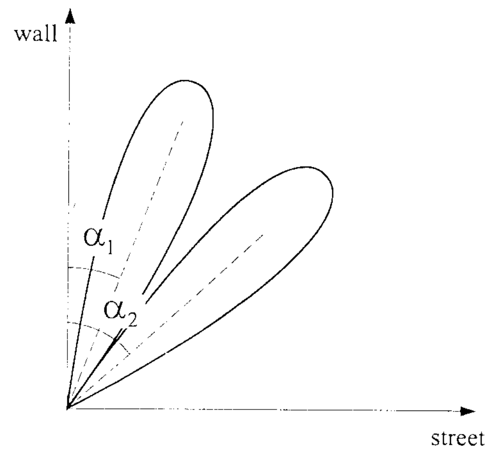

Fig. 1. Base-station antenna-beam orientations.

The aim of this study is to apply a ray propagation model in correlation analysis of received signals of independent antenna beams pointing to different directions. An optimal pair of directed antenna beams is searched based on signal correlation values in order to maximize diversity gain in both LOS and NLOS situations. The influence of the antenna parameters as beam orientation from the wall direction, separation of the main beam directions, and 3-dB beamwidth of the base-station antenna on signal correlations is studied. In addition, two different base-station antenna locations have been simulated to find out the effect of the location together with the above-mentioned parameters on correlations in microcells. In simulations, the narrow-band radio propagation channel at the frequency band 900 MHz is considered, ignoring delay spread and polarization properties of the signal. The signal at the base-station end can separately be detected by individual antenna beams in the uplink direction, and depending on the location of the mobile station (MS), one of the beams is superior to the other. Diversity gain associated with two separate beams

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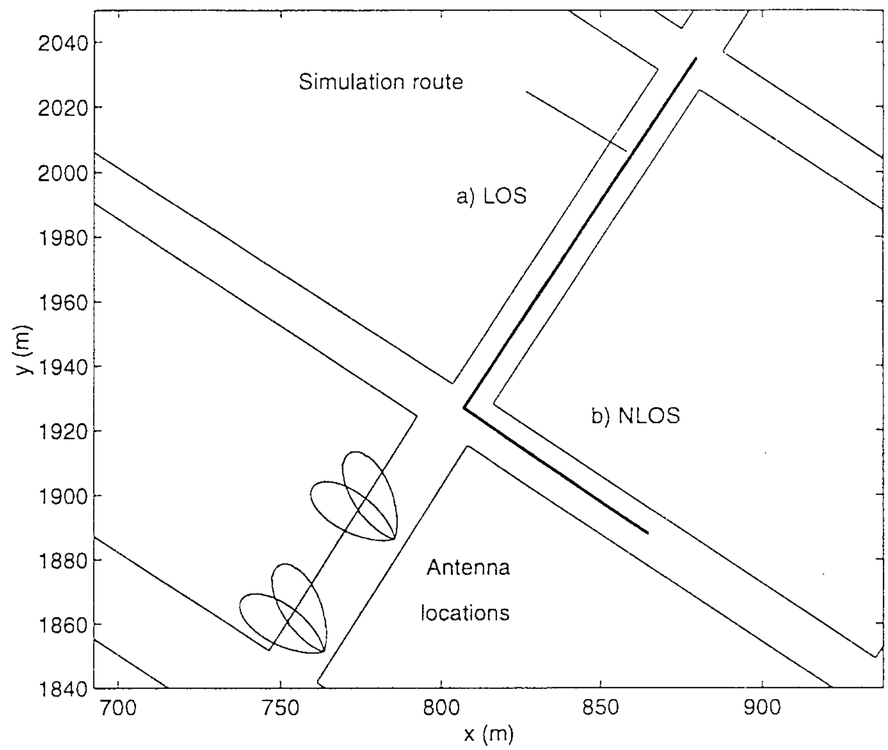

Fig. 2. Base-station antenna array locations and simulation path.

can thus be obtained by applying, e.g., an adaptive antenna array whose radiation pattern can be optimized by a correlation analysis.

II. Ray Propagation Simulations

The objective of ray propagation simulations is to analyze signal correlations between two antenna beams pointed to different directions in order to find out the antenna parameters producing maximum diversity gain in both LOS and NLOS paths. The signal correlations of two independent antenna beams are computed as a function of α_1 and α_2, which both vary 0° to 45° in steps of 5° from the direction toward the building across the street (see Figs. 1 and 2). Hence, too-strong signal propagation along the street is avoided. Two antennas with different beamwidths—one having a wide and the other a narrow radiation pattern—are tested separately in each simulation. The antennas used in simulations are located in the middle of the street intersections or are close to the intersection as shown in Fig. 2. The following four separate cases are computed:

- $\mathbf{A}_\mathrm{w}$ base station in the middle of the intersections: a wide-beam antenna;
- $\mathbf{A}_\mathrm{n}$ base station in the middle of the intersections: a narrow-beam antenna;
- $\mathbf{B}_\mathrm{w}$ base station at the intersection: a wide-beam antenna;
- $\mathbf{B}_\mathrm{n}$ base station at the intersection: a narrow-beam antenna.

These four cases were chosen in order to enable one to compare the performance of the base-station antennas which have different beamwidths and positions. In each simulation, the base-station antenna array was in a typical microcellular environment 4 m away from the wall at the height of 4 m. The signal propagation prediction was made by a software utilizing a ray propagation model and the uniform theory of diffraction (UTD). The simulations were made using complex radiation patterns of different antennas. Thus, amplitude and phase directivities corresponding to different arrival directions were included. The digital map of the urban environment seen in Fig. 2 includes topographic and morphographic data as well as building shape information (width and height) of the city area in Helsinki. Simulations were made along the route, also indicated in the same Fig. 2, containing: 1) LOS and 2) NLOS paths, which both were analyzed separately.

Three- and seven-element linear arrays providing a wide (52° half-power beamwidth) and narrow (22.5° half-power beamwidth) horizontal radiation patterns for the base-station antenna were studied. These two beamwidths were chosen because antenna radiation patterns cannot be too narrow or wide ones in practice in mobile networks. The coverage area of the base station is reduced remarkably if beamwidth is $\ll$30° [1], and, correspondingly, interferences increase if beamwidth is $\gg$60°. Therefore, the optimized beamwidth is not exact value, but related to a compromise of coverage, interference, and signal cross-correlation requirements. Thus, narrow- (22.5°) and wide-beam (52°) antenna patterns represent practical coverage and interference limitations of the beamwidth. Both antenna arrays had a reflector behind the elements, thus avoiding a backlobe and power radiation behind the base station. The normalized radiation patterns corresponding to either wide or narrow beams are illustrated in Fig. 3. The sidelobe levels of both antennas are at least −25 dB. Both three- and seven-element antennas produce two

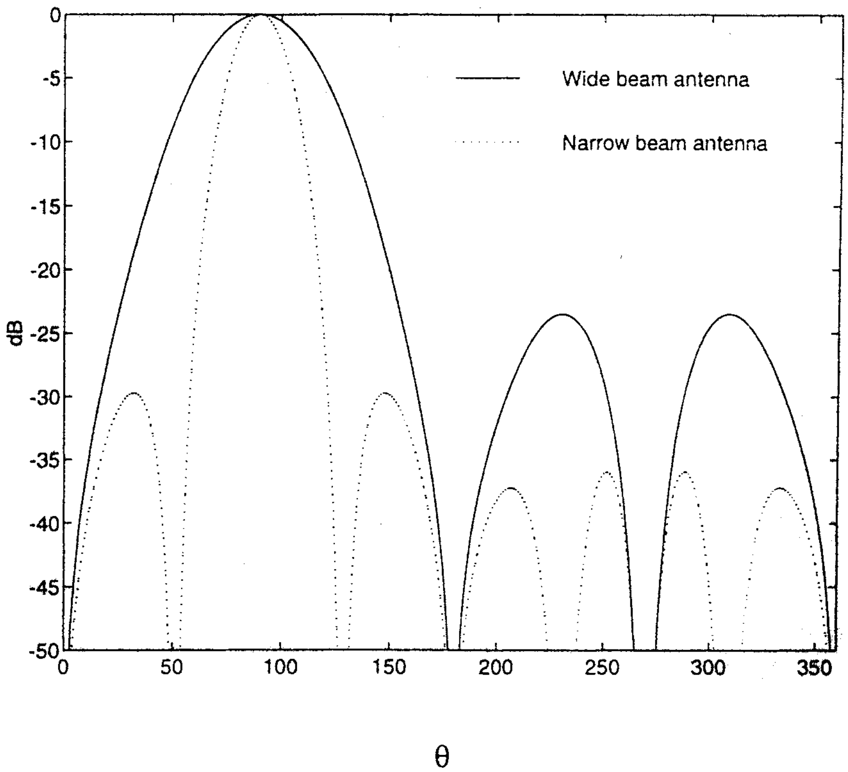

Fig. 3. Horizontal patterns of test antennas in decibel units.

independent beams in different directions. In practice, these beams can be realized by applying digital signal processing (DSP) techniques, or more straightforwardly, using two separate receivers. Signal correlations and diversity gains in microcells (illustrated in Fig. 2) were studied using the above-mentioned simulation environment and antenna patterns with different orientation angles α_1 and α_2.

III. Results

The correlations of the field-strength levels for the LOS path received by two independent beams as a function of their directions α_1 and α_2 in case $\mathbf{A}_\mathrm{w}$ with a wide radiation pattern are presented in Fig. 4 and, for the NLOS path, in Fig. 5. The same results with narrow beams (in case $\mathbf{A}_\mathbf{n}$) for LOS and NLOS situations are shown in Figs. 6 and 7, respectively. Each curve of signal correlation values has been calculated by fixing one beam to angle α_1 and allowing the other to scan angles 0° to 45° (α_2) in steps of 5°. The maximum correlation value 1.0 is obtained when both beams are pointed to the same direction ($\alpha_1 = \alpha_2$). The orientation angles α_1 and α_2 are measured from the wall direction as in Fig. 1. Figs. 4–7 show that the mutual correlation of wide beams is generally stronger over a broader beam separation angle than that for narrow beams, as could intuitively be expected. The reason for this is the wider complex radiation pattern. However, for both antenna types the first correlation minimum can be found approximately when the beam-separation angle corresponds to the half-power beamwidth.

When optimizing a double-beam reception, a low-signal correlation is only one requirement for the independent antenna beams. In addition, they both have to be used equally in an average to maximize the efficiency of the antenna and the cell size. Figs. 8 and 9 show which beam direction (α_1 or α_2) receives superior field-strength level in percentages in LOS and NLOS paths, respectively, when two independent narrow beams (case $\mathbf{A}_\mathbf{n}$) with different orientations angles are used. The relative usages of different beam directions in Figs. 8 and 9 are defined by

$$P(\alpha_1 > \alpha_2) = 100 * \frac{\mathrm{T1}}{\mathrm{T1} + \mathrm{T2}} \tag{1}$$

where:

- T1 total time that the field strength of antenna α_1 is higher than that of antenna α_2;
- T2 total time that the field strength of antenna α_2 is higher than that of antenna α_1.

It can be seen that in both LOS and NLOS paths, one beam is usually dominating when beam separation is more than 3-dB beamwidth. Hence, the correlation minimum and a simultaneous balance in the use of two beams in both LOS and NLOS can be found based on the maximum half-power beamwidth separation of the independent beams if a single antenna pattern is not too wide. The field-strength levels in LOS and NLOS paths received by the narrow-beam antenna with orientations $\alpha_1 = 0°$ and $\alpha_2 = 5°$, based on the equal use of two beams (see Figs. 8 and 9) and the maximum beam separation equal to the half-power beamwidth, are seen as an example in Figs. 10 and 11, respectively. The dotted line corresponds to the orientation of $\alpha_1 = 0°$, and the solid line to the orientation $\alpha_2 = 5°$ in Figs. 10 and 11.

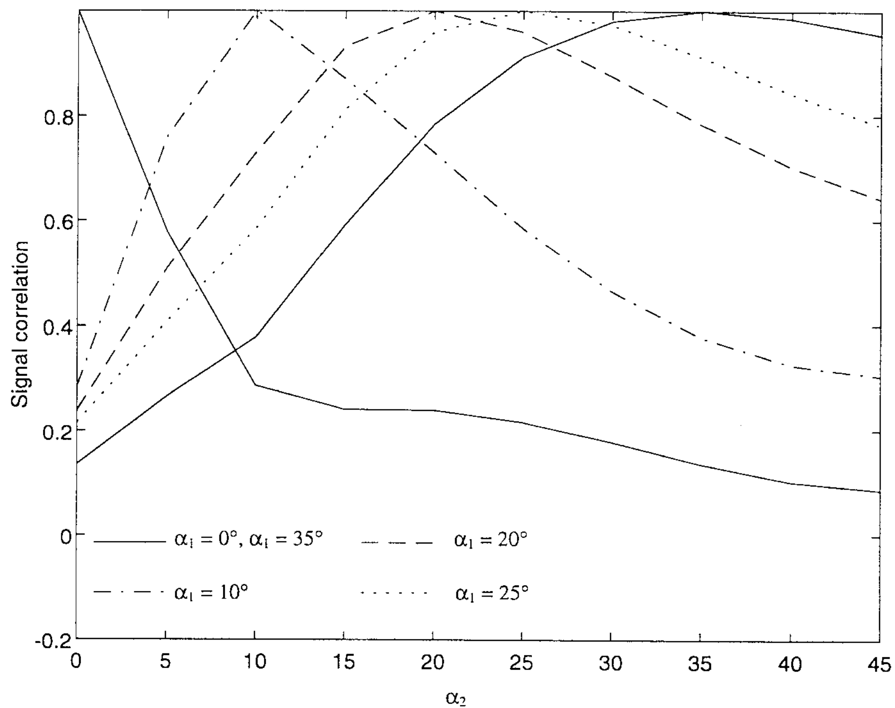

Fig. 4. Signal correlations of different orientation angles α_1 and α_2 in LOS path: case $\mathbf{A}_{\rm w}$.

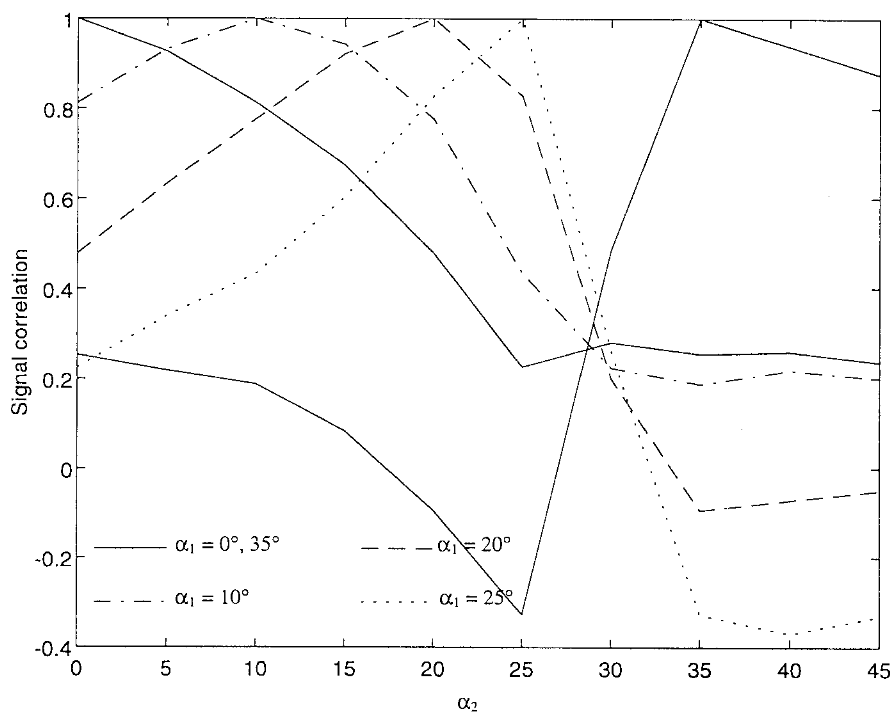

Fig. 5. Signal correlations of different orientation angles α_1 and α_2 in the NLOS path: case $\mathbf{A}_{\rm w}$.

An effort was made to find the correlation minimum for LOS and NLOS paths with equal use of two independent antenna beams as a function of beam directions α_1 and α_2. Signal correlations of these beams with different orientations from the wall direction were compared using a half-power beamwidth separation corresponding to maximum 25° for the wide-beam antenna and 10° for the narrow-beam antenna. In different orientations with the wide beams, correlation values lower than 0.2 (Figs. 4 and 5) were achieved in both LOS and NLOS situations. The correlation minimum can be found with beam orientations $\alpha_1 = 0°$ and $\alpha_2 = 10°$ for the LOS path and with orientations $\alpha_1 = 25°$ and $\alpha_2 = 35°$ for the NLOS path. When the narrow-beam antenna is considered, Fig. 6 shows that minimum correlation in LOS path can be found, e.g.,

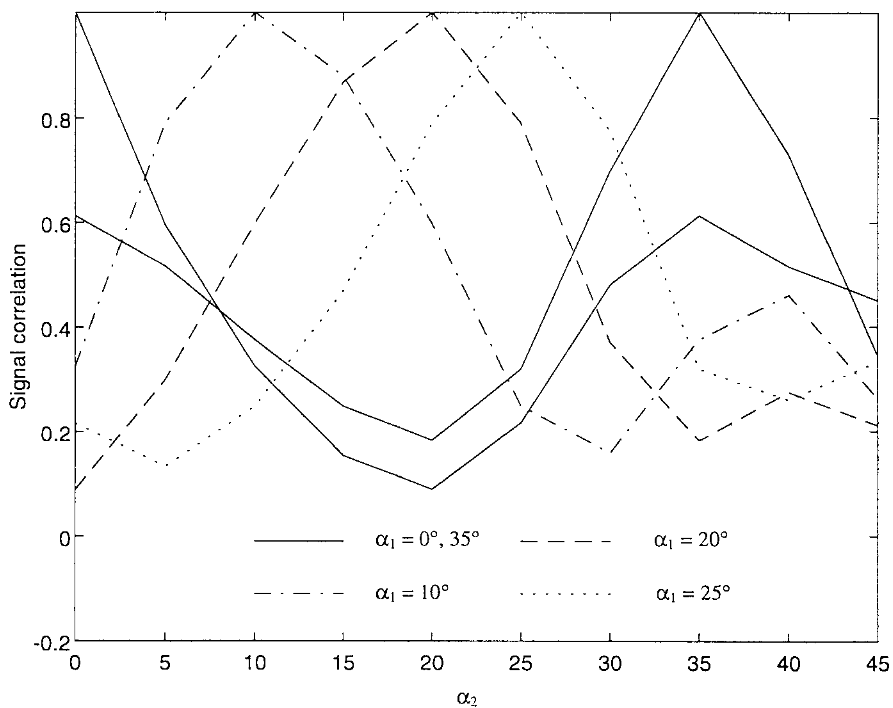

Fig. 6. Signal correlations of different orientation angles α_1 and α_2 in the LOS path: case $\mathbf{A}_{\rm n}$.

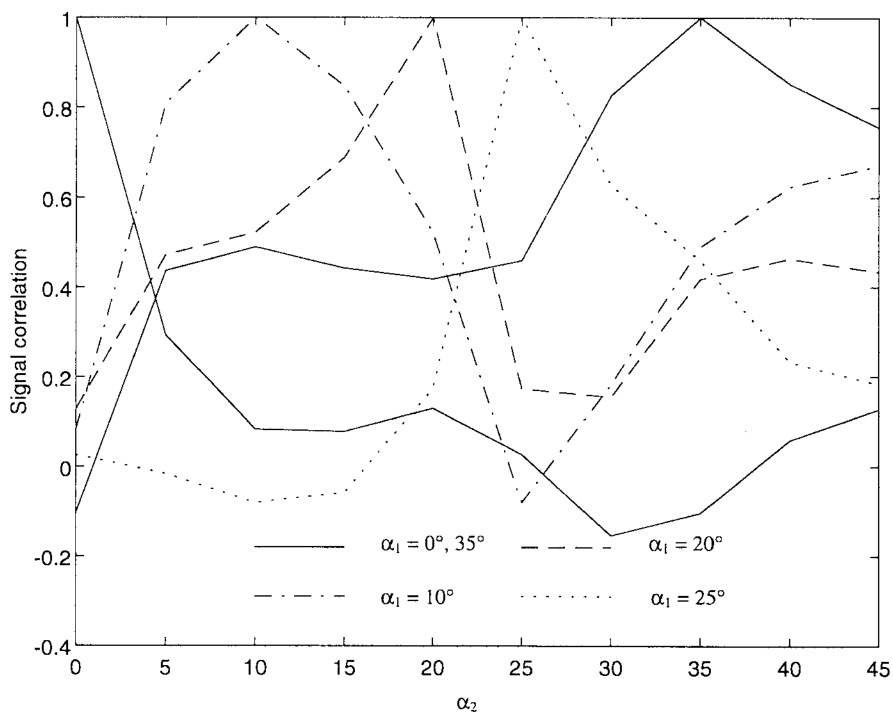

Fig. 7. Signal correlations of different orientation angles α_1 and α_2 in the NLOS path: case $\mathbf{A}_{\rm n}$.

using beam orientations $\alpha_1 = 0°$ and $\alpha_2 = 10°$. A minimum correlation in the NLOS path can also be achieved using antenna beams with orientations $\alpha_1 = 0°$ and $\alpha_2 = 10°$ or $\alpha_1 = 15°$ and $\alpha_2 = 25°$ from the wall direction (Fig. 7). Thus, correlation minimums coincide for LOS and NLOS paths ($\alpha_1 = 0°$ and $\alpha_2 = 10°$) with a narrow-beam antenna while minimum correlation for LOS and NLOS paths cannot be obtained simultaneously with wide-beam antenna. Hence, an optimal direction of the antenna beams can be obtained when the narrow-beam antenna is used, and these directions can be utilized to achieve diversity gain. Based together on correlation values in Figs. 6 and 7 and on the comparison of signal levels in Figs. 8 and 9, the lowest correlations with equal usage of both beams for both LOS and NLOS situations can be achieved

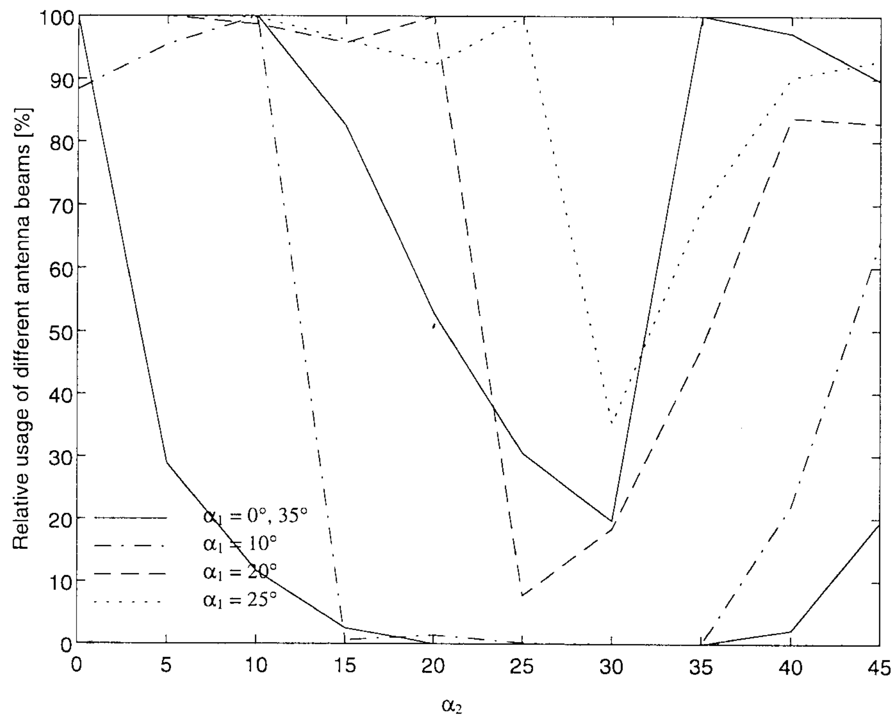

Fig. 8. Relative usage of different antenna beams in LOS path: case $\mathbf{A}_{\rm n}$.

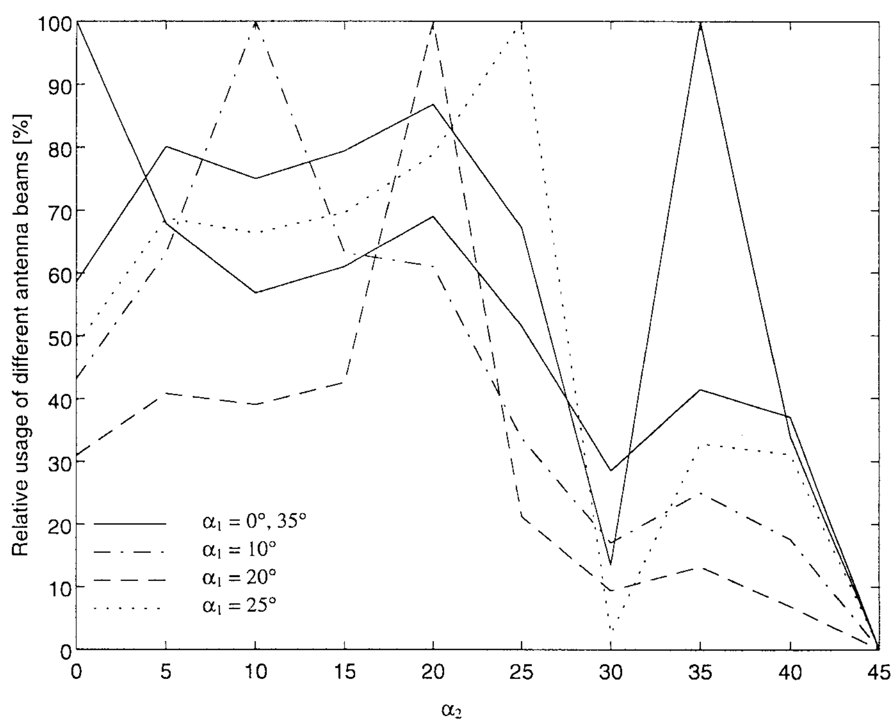

Fig. 9. Relative usage of different antenna beams in the NLOS path: case $\mathbf{A}_{\rm n}$.

by the narrow-beam antenna with beam orientations $\alpha_1 = 0^\circ$ and $\alpha_2 = 5^\circ$ to 10° from the wall direction.

In the first two cases ($\mathbf{A}_{\rm w}$ and $\mathbf{A_n}$), the base-station antenna was located in the middle of the street intersections (Fig. 2), and the lowest signal correlations were achieved by the narrow-beam antenna with beam orientations $\alpha_1 = 15^\circ$ and $\alpha_2 = 25^\circ$ from the wall direction. The last two cases ($\mathbf{B}_{\rm w}$ and $\mathbf{B_n}$) were simulated with wide- and narrow-beam base-station antennas located close to the intersection (Fig. 2) in order to see the influence of the location of the base-station antenna. Signal correlation values were computed and are illustrated in Figs. 12 and 13 with the narrow-beam antenna (case $\mathbf{B_n}$) for both LOS and NLOS paths, respectively. The received signals for both LOS and NLOS paths in case $\mathbf{B_n}$

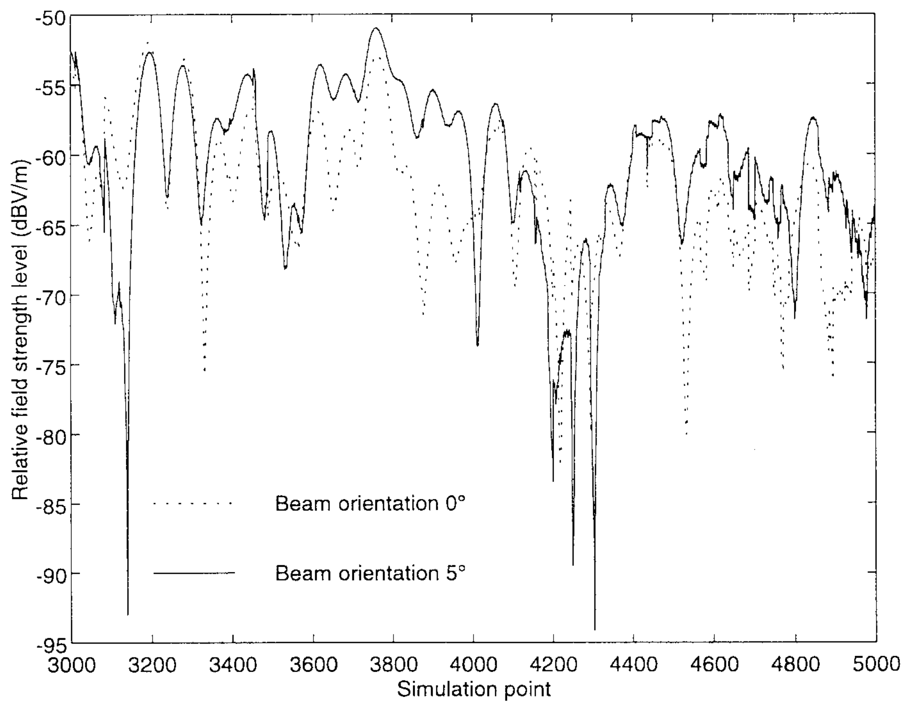

Fig. 10. Relative field strength, LOS path, and beam orientations 0° and 5°: case $\mathbf{A}_\mathrm{n}$.

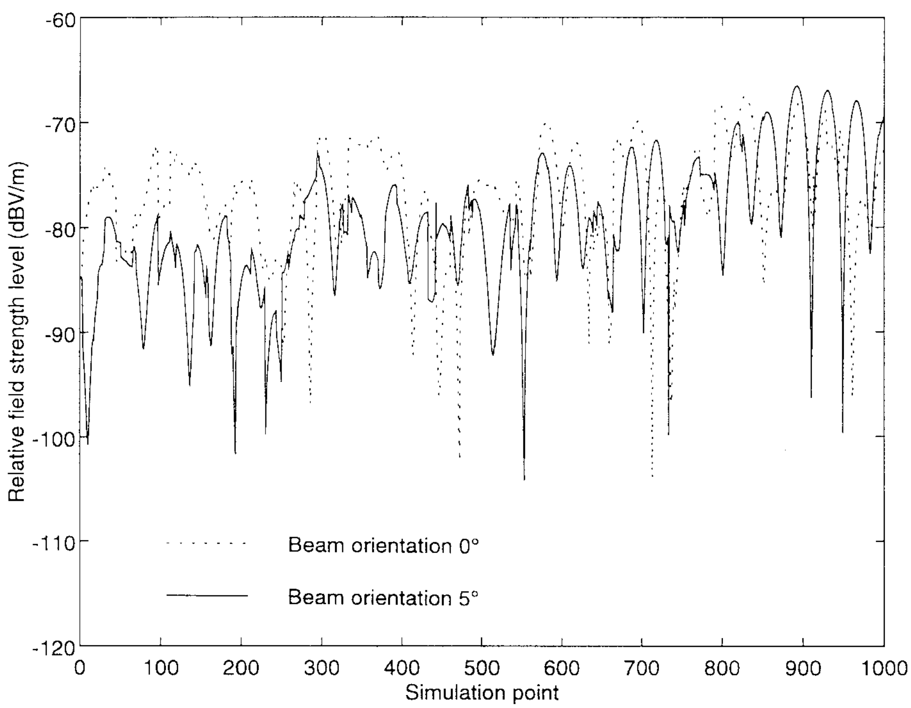

Fig. 11. Relative field strength, NLOS path, and beam orientations 0° and 5°: case $\mathbf{A}_\mathrm{n}$.

correlate slightly better compared to the case $\mathbf{A}_\mathrm{n}$, where the base-station antenna was located in the middle of the street intersections (Figs. 6 and 7). The optimal beam orientations cannot be seen as clearly as in case $\mathbf{A}_\mathrm{n}$. Hence, antenna location in the middle of the intersections seems to be better for achieving low correlations with the narrow-beam antenna, and the same result can also be shown for the wide-beam antenna.

IV. Application Diversity

A narrow-beam antenna (case $\mathbf{A}_\mathrm{n}$) with beam orientations $\alpha_1 = 0°$ and $\alpha_2 = 5°$ was selected as an example to demonstrate diversity gain properties of two independent beams. Beam orientations α_1 and α_2 were chosen based on low-signal correlation values both for LOS and NLOS paths (Figs. 6 and 7) and the equal use of both beams (Figs. 10 and 11).

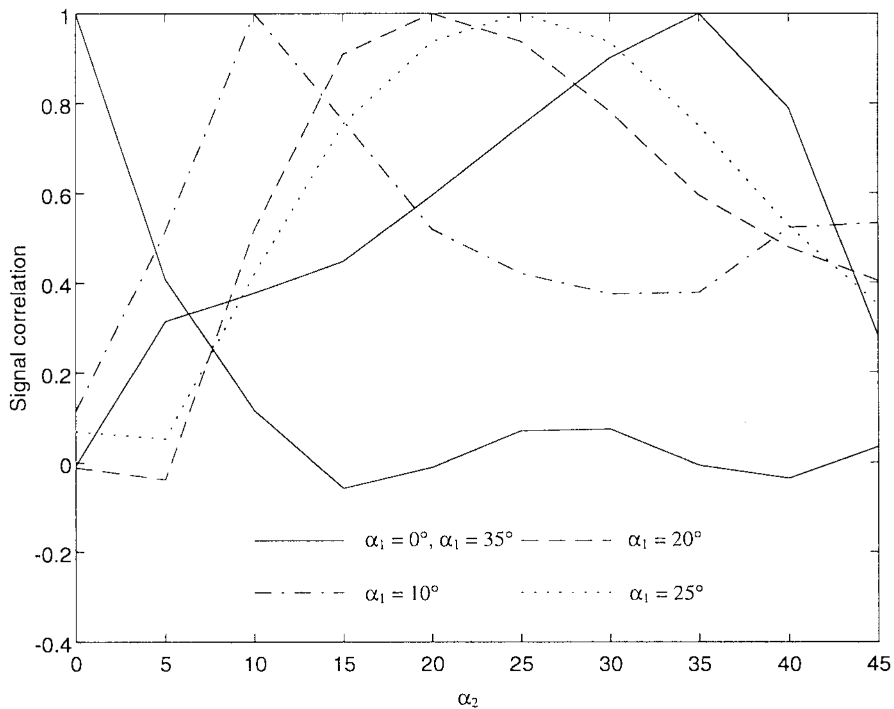

Fig. 12. Signal correlations of different orientation angles α_1 and α_2 in the LOS path: case $\mathbf{B}_\mathrm{n}$.

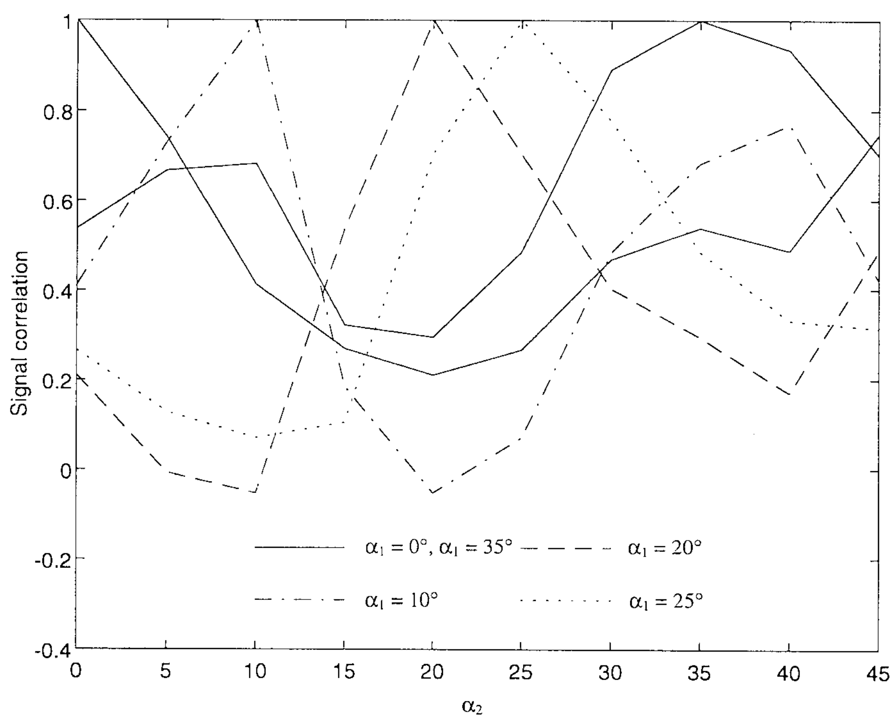

Fig. 13. Signal correlations of different orientation angles α_1 and α_2 in the NLOS path: case $\mathbf{B}_\mathrm{n}$.

According to the results, a narrow-beam antenna located in the middle of the street intersections with beam orientations $\alpha_1 = 0°$ and $\alpha_2 = 5°$ minimizes correlation and maximizes the use of both beams in LOS and NLOS paths. Fig. 14 illustrates signal probabilities of both beams in LOS path in uplink direction. The same signal probabilities in the NLOS path can be seen in Fig. 15. The dotted line corresponds to the narrow-beam base-station antenna with an orientation of $\alpha_1 = 0°$ and the solid line with an orientation of $\alpha_2 = 5°$ in both Figs. 14 and 15. The solid line with circles represents the stronger of the received signals associated with the base-station antenna beams in two different orientations along the route. Diversity gain in LOS and NLOS paths can be seen in Figs. 14 and 15 by comparing the solid line with circles

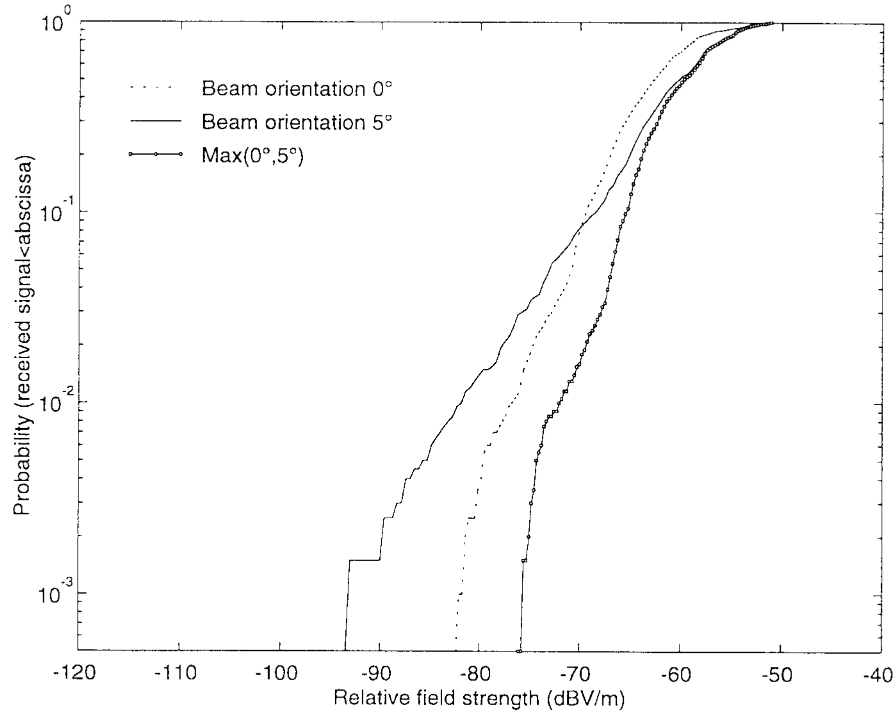

Fig. 14. Probability function of the relative field-strength level. The solid line with circles corresponds to the case in which diversity gain has been exploited, LOS path, and beam orientations 0° and 5°: case $\mathbf{A}_{\mathrm{n}}$.

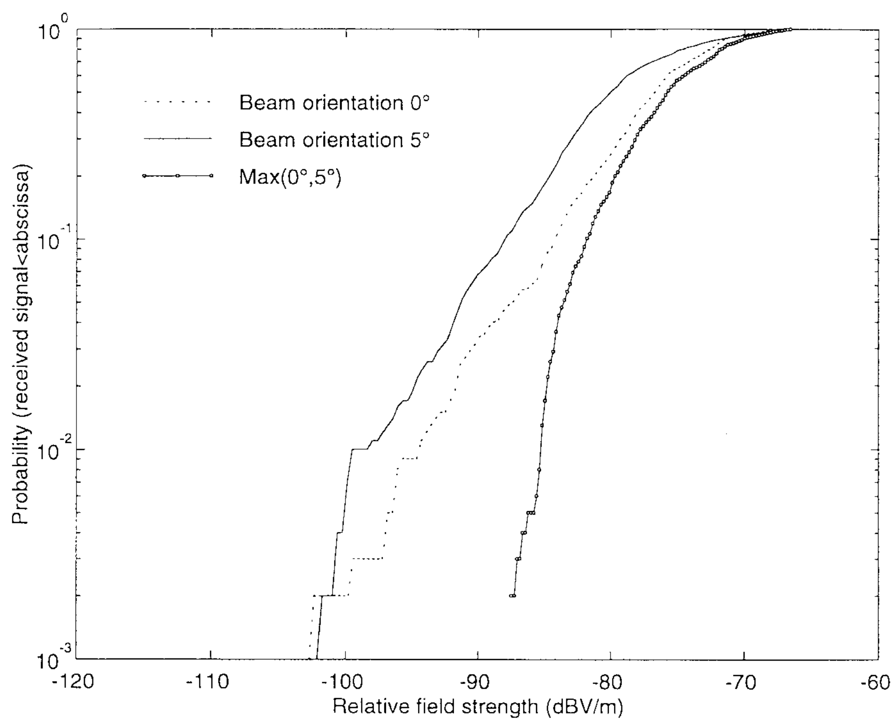

Fig. 15. Probability function of the relative field-strength level. The solid line with circles corresponds to the case in which diversity gain has been exploited, NLOS path, beam orientations 0° and 5°: case $\mathbf{A}_{\mathrm{n}}$.

to the dotted and solid lines. When the received signal has to exceed a certain fixed threshold value, for instance, with probability 0.99, two differently directed beams provide at least 3-dB gain in the LOS path (Fig. 14) and 8-dB gain in the NLOS path (Fig. 15) compared to the situation where a beam pointed to the direction $\alpha_1 = 0°$ or $\alpha_2 = 5°$ is used only. The diversity gains of other beam orientations with different beam separations were also studied, and the obtained results show that the maximum diversity can be achieved using beam directions $\alpha_1 = 0°$ and $\alpha_2 = 5°$ when the narrow-beam

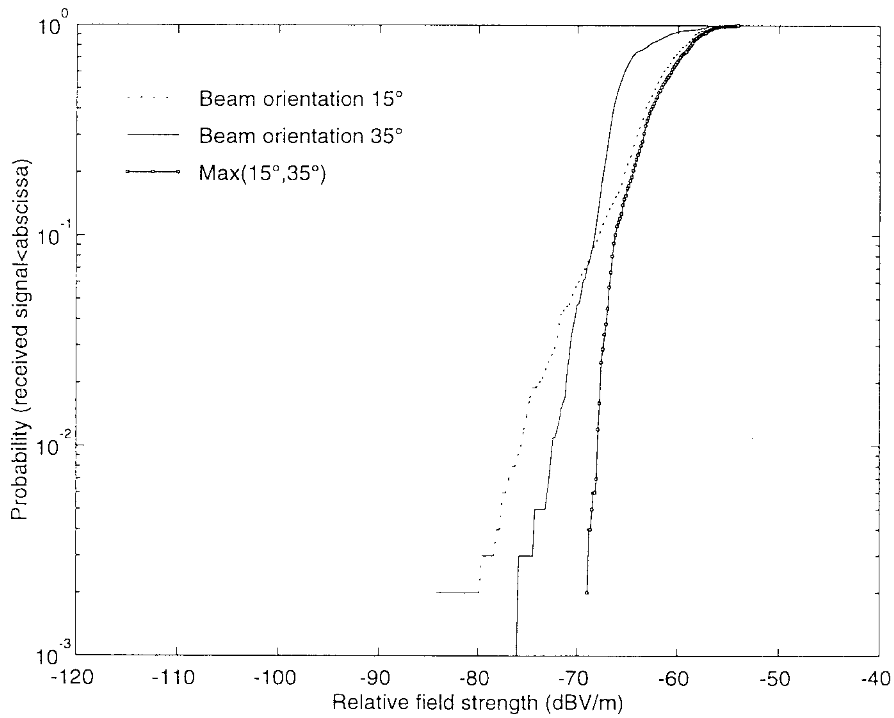

Fig. 16. Probability function of the relative field-strength level. The solid line with circles corresponds to the case in which diversity gain has been exploited, NLOS path, and beam orientations 15° and 35°: case $\mathbf{A}_\mathrm{w}$.

antenna is used. In other beam directions, signal correlation grows (Figs. 6 and 7) or signal levels are not at an equal level (Figs. 8 and 9) and diversity gain disappears.

In order to show the effect of the beamwidth on diversity gain, the probability functions of the relative field-strength levels received by the wide-beam antenna (case $\mathbf{A}_\mathrm{w}$) in the NLOS situation are presented in Fig. 16. With wide beams, correlation minimums in the LOS and NLOS paths do not coincide (see Figs. 4 and 5) and diversity cannot be obtained in the LOS and NLOS paths simultaneously. The diversity gain was maximized for the NLOS path due to its lower signal level. The beam orientations $\alpha_1 = 15°$ and $\alpha_2 = 35°$ were selected based on the low-signal correlation values (from Figs. 4 and 5) and equal use of both beams. Diversity gain is 3 dB in the NLOS path (Fig. 16) when probability 0.99 is exceeded compared to the situation where antenna-beam direction $\alpha_1 = 15°$ or $\alpha_2 = 35°$ is used merely. The antenna beam with orientation $\alpha_2 = 35°$ is completely superior in the LOS path and diversity gain disappears totally.

V. Conclusions

Signal correlations of two independently directed antenna beams were computed based on ray propagation simulations in microcellular environment. Both narrow- and wide-pattern antennas in two different antenna array locations were studied. Simulated results indicate that signal correlations depend on the beamwidth of the antenna pattern, the separation angle and the orientations of the antenna beams. The location of the base-station antenna also has an effect on signal correlations. The maximum diversity gain in both LOS and NLOS situations can be found based on correlation analysis. According to the results, the maximum separation angle of the beams may not exceed the half-power beamwidth, and it should be optimized to provide low correlation. The obtained results show that the narrow-beam antenna located in the middle of the street intersections with beam orientations $\alpha_1 = 0°$ and $\alpha_2 = 5°$ produce the maximum diversity in LOS and NLOS paths.

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