Angle and Space Diversity Comparisons in Different Mobile Radio Environments

Patrick L. Perini, *Member, IEEE*, and Christopher L. Holloway, *Member, IEEE*

***Abstract*— The angle diversity performances of two types of high-gain multibeam antennas—24 vertically polarized 15° beams and 12 vertically polarized 30° beams—were tested and compared to the space-diversity performances of traditional sector antenna configurations. The antennas were tested at 850 MHz in dense urban and rural cellular mobile radio environments. A vehicle equipped with a mobile transmitter was driven in the coverage area, while the received signal strength (RSS) was recorded on multiple receiver channels attached to multibeam and sector antennas at the base site. The RSS data recorded included fast (Rayleigh) fading and was averaged into local means based on the mobile's position/speed. The fast fading was extracted from the recorded RSS and the fading distributions of the two multibeam antennas tested were studied in two distinctly different mobile environments. Fading cumulative distributions for the angular diverse antennas were compared to those of spatially diverse antennas. Diversity gain was calculated and compared to traditional space diversity in these mobile environments. Results in urban environments indicated that angular diversity performance was comparable to space diversity (∼-8 dB improvement). Rural tests typically suggested that both space diversity and angular diversity provided little or no (<2 dB) fading reduction. A description of the experiment, data reduction and analyses, and calculation of diversity gain are presented. The motivation for this experiment is the application of fixed multiple beam antennas (FMBA) in cellular radio and digital personal communication systems.**

***Index Terms*—Mobile communication, multibeam antennas.**

I. Introduction

IN cellular mobile radio communications, the multiple propagation paths of the mobile signal to the radio base-station antenna results in fading of the mobile signal. This multiple-path propagation channel, often referred to as a Rayleigh-fading channel [1], [2] experiences large drops in the received signal strength. These fading outages can be as large as 20–30 dB and occur rapidly over time as the mobile velocity increases. Depending on the severity of the fading, a fade margin often is necessary in the mobile link requirements to maintain a high degree of reliability in the communications link. Without this fade margin, the radio link is susceptible to increased noise in analog frequency modulated (FM) cellular systems and higher bit error rates (BER) for digital personal communication systems (PCS). In either case, reliable voice quality degrades, posing a serious concern for the mobile service provider.

Manuscript received April 1, 1997; revised January 23, 1998.

P. L. Perini is with U.S. West Advanced Technologies, Boulder, CO 80303 USA.

C. L. Holloway is with the Institute for Telecommunication Sciences, U.S. Department of Commerce, Boulder, CO 80303 USA.

Publisher Item Identifier S 0018-926X(98)04867-4.

To reduce these fading outages, receive base-station antenna diversity is used at the base site to obtain multiple Rayleigh channels, which can then be combined in a receiver to obtain a maximum received signal. Typically, antenna diversity is used only at the base station and, hence, only the up-link fade margin is improved. The most common form of antenna diversity used in cellular systems today is two-branch horizontally separated or space diversity. In today's advanced mobile phone system (AMPS), the base-station receiver is equipped with selection diversity circuitry to select the maximum of the two received signals. Other digital PCS base-station receivers employ maximum ratio combiners that sum the diversity channels using a weighted combining algorithm. Conventional space diversity uses two spatially separated antennas (usually a horizontal separation) and each antenna covers the same angular region. For a omnidirectional cell site, there are two space-diversity antennas, each covering 360°. For a three sector site, the two diversity antennas would each cover 120° per sector.

However, independent of the receiver diversity combiner, antenna diversity can be implemented in different antenna configurations other than the horizontal spatially separated antenna configuration typically used in today's cellular systems. A different antenna diversity configuration—angle diversity—is considered as an alternative to space diversity. In angle diversity, antennas with narrow beamwidths are postioned in different angular directions or regions. The two main reasons narrower beams are used are to increase the gain of the base-station antenna and to provide angular discrimination that can reduce interference.

Note that there is a tradeoff between the narrow beamwidth (or gain) and the number of antenna beams, and, hence, the complexity and size of the antenna, which produces the multiple narrow beams. For example, if we use very-high-gain antenna beams with 10° beamwidths, we need 36 antenna beams pointed in 36 different directions or regions to achieve 360° omnidirectional coverage. However, with a lower gain 30° beam, only 12 beams pointed in 12 different regions are needed for omnidirectional coverage. Although the higher gain beams produce more gain and yield better angular discrimination, the antenna which produces them is larger and heavier than the antenna, which produces fewer multiple lower gain (or wider beamwidth) beams. The larger antennas increase tower loads and infrastructure costs and make it more difficult to get local approval or zoning for tower installation.

Performance of angle diversity has been widely reported [3]–[9]. However, much of the work [3]–[6] focuses on its application for European terrestrial microwave hops greater

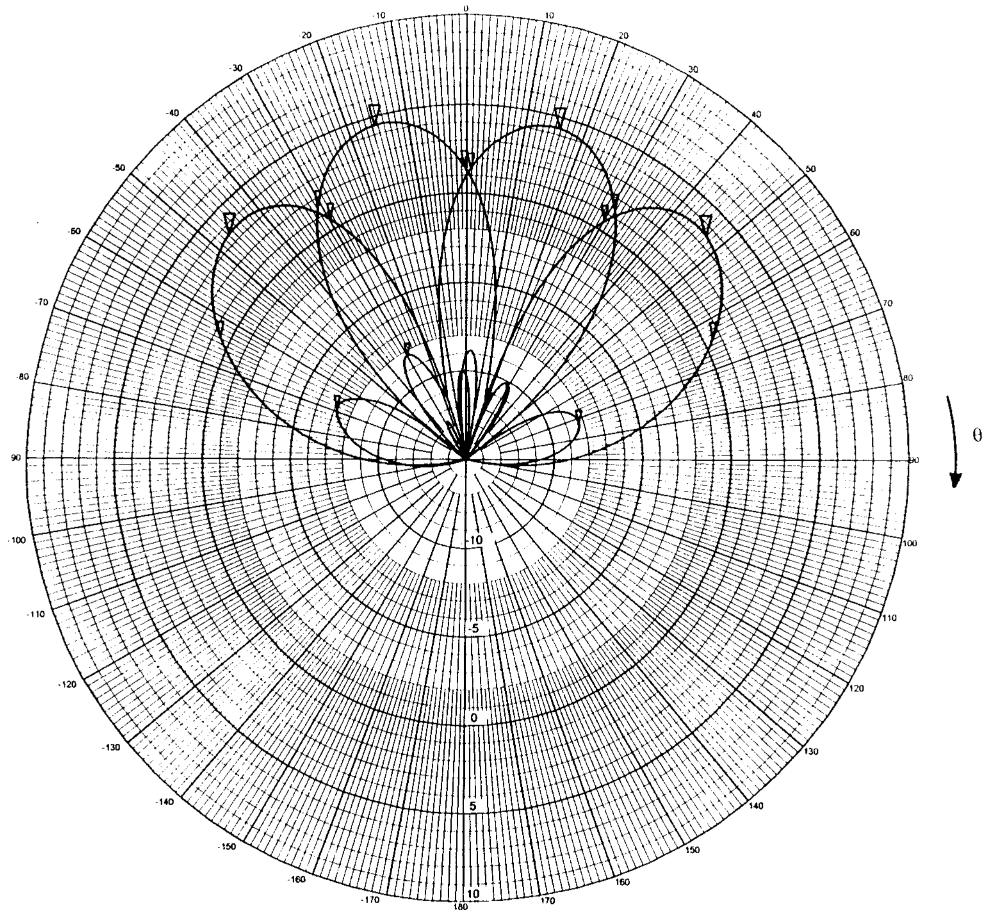


Fig. 1. Multibeam antenna radiation plot of 30° FMBA—azimuth pattern.

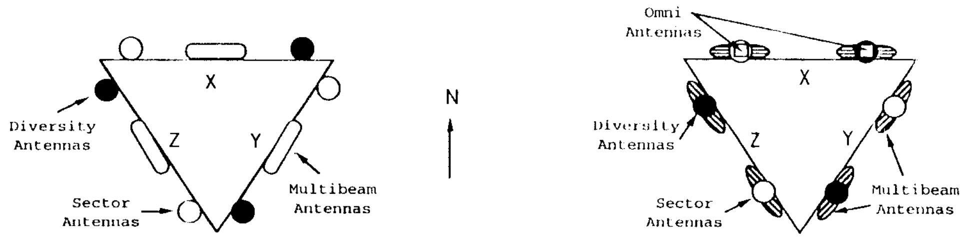
than 30 km and at frequencies ranging from 3 to 6 GHz. This work often employs two or three ray models [4], [5] to determine the effectiveness of angle diversity. Other related work [10] discusses angle-of-arrival statistics for similar microwave hops. However, these works are not applicable to cellular mobile radio systems. While angle diversity is not common in terrestrial cellular systems, this paper assesses the performance of angle diversity for cellular applications.

In this paper, we examine cumulative distribution functions (CDF) of the fading mobile signal on both angular and spatially diverse antenna channels to compute and compare the diversity gain of angle and space diversity. Their performance is evaluated in two distinctly different cellular environments: 1) dense urban and 2) flat rural terrain. The expectation is that angle diversity should be effective in dense urban cellular environments where there is significant scattering of the mobile signal resulting in large variations in the angle of arrival of the base station's received signal. However, in rural cellular environments where there is direct line-of-sight (LOS) reception of the mobile with little or no scattering, we expect that angle-diversity performance will be poor due to large differences in the mean received signal on the different angular-diverse antenna beams.

II. Experimental Setup

Cellular towers typically use a triangular tower top configuration to mount the base station receive antennas. This triangle provides for a separation of the cell into three 120° sectors, each covered by two receive antennas mounted on each side of a sector of the tower top triangle. Two sector antennas, each typically with a 90–120° beamwidth, provide space diversity for each of the three sectors and are normally horizontally separated by ten wavelengths on each side of the tower top triangle. In this experiment, we duplicated the triangle antenna tower configuration with two branch horizontal space diversity so we can compare traditional space-diversity performance to that of angle diversity.

As mentioned previously, with angular-diverse antennas there is a tradeoff between the beamwidth (or gain) and number of beams required to achieve cellular coverage. In making such a tradeoff for this experiment, two different narrow horizontal beamwidths were used: 1) 30° beams and 2) 15° beams. These antenna beams will have significantly more gain (4–7 dB) than a sector antenna, but the number of antenna beams required will not be too large as to make the antenna design impractical for cellular deployment. In this angle-diversity antenna configuration, 12 30° beams or 24 15° beams are required for 360° omnidirectional coverage. To reduce the overall antenna size of these multiple beam antennas, each sector has a fixed multiple beam antenna (FMBA) panel which produces the necessary number of beams to cover a single 120° sector. In our three-sector tower-top configuration, each side of a sector requires a single FMBA panel, which produces either four 30° beams or eight 15° beams.



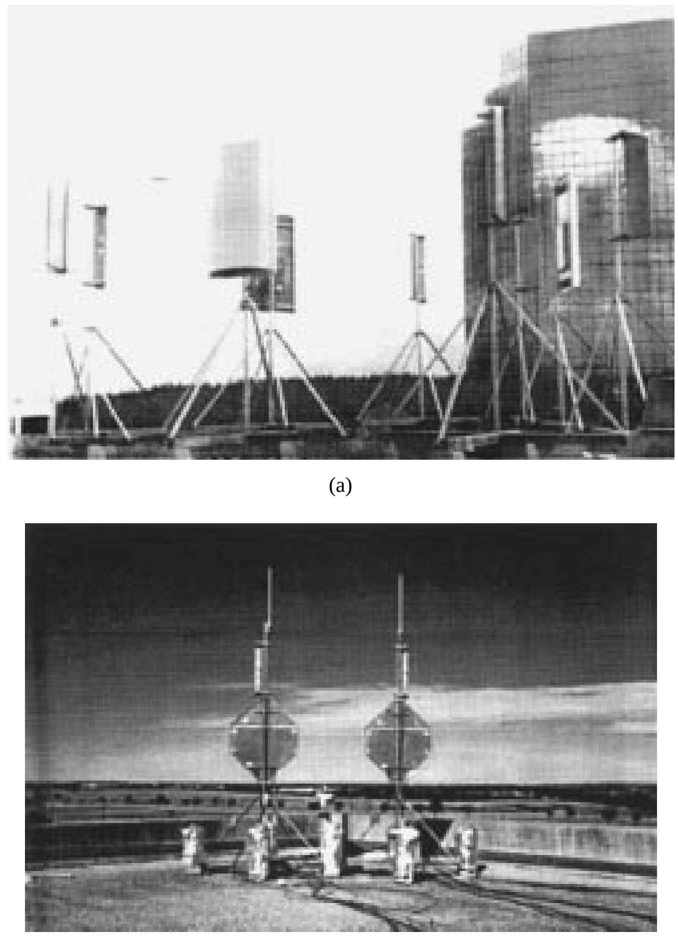
(a) (b)

Fig. 2. Top view of antenna configurations. (a) Dense urban antenna base site location—Seattle, WA. (b) Rural flat terrain antenna base site location—Fort Worth, TX.

The type of FMBA panels tested were butler matrix-fed planar arrays [11] consisting of 1) four 30° beams per panel and 2) eight 15° beams per panel. The azimuth pattern for the four 30° beam FMBA panel is shown in Fig. 1. As shown in Fig. 1, the four 30° beams point in different azimuth directions ($-45°$, $-15°$, $+15°$, $+45°$) from the sector boresight in order to provide coverage over the entire sector. A similar distribution of eight, 15° beams over a 120° sector is also achieved with the 15° FMBA panel. Note the elevation or vertical beamwidth is constant at 15° for all beams produced by the 15° and 30° FMBA panels. Typical peak gain is 17 dBi for the 30° beams and 20 dBi for the 15° beams.

Separate tests were performed using the 30° and 15° multibeam antenna panels placed in this typical three-sector triangle configuration. The three sector antenna configurations for the two different cellular environments are shown in Fig. 2(a) and (b). For both the 30° and 15° tests, the sector antennas remained unchanged, and the 30° or 15° multibeam panels were placed between the sector antennas as shown in Fig. 2. Note that the sides of the sectors (i.e., tower faces) are designated with the letters X, Y, and Z. In cellular, we typically denote the top or northward sector as X and the Y and Z faces are labeled clockwise from the X face. Consequently, the Y face or Y sector typically points southeast and the Z face points southwest. The dense urban tests were conducted in downtown Seattle and Bellevue, WA, while the rural flat terrain tests were conducted north of Fort Worth, TX. In both tests, standard cellular sector antennas were placed on each tower face, along with a second diversity sector antenna approximately 3 m (10 ft) away to provide a space diversity for the X, Y, and Z sectors. The sector antennas used for the space-diversity comparison had a 92° azimuth beamwidth, a 15° elevation beamwidth, and approximately 13-dBi peak gain. Photos of the urban and rural antenna configurations are shown Fig. 3(a) and (b), respectively.

The outputs from the antenna ports for the three antenna configurations (15° beams, 30° antenna beams, and sector antennas) were connected to independent radio receivers at the base-site location and the received signal strength from the mobile transmitted signal was recorded. For this experiment, a mobile vehicle was equipped with a rooftop mobile antenna transmitting a 20-W continuous-wave (CW) radio signal at a frequency of 850 MHz. A global positioning system (GPS) receiver provided vehicle location and velocity information as the mobile RSS was recorded at the antenna base site. With GPS, the vehicle position was synchronized in time



(a)

(b)

Fig. 3. Photos of antenna base sites. (a) Seattle, WA, antenna location. (b) Fort Worth, TX, antenna location.

to the RSS data acquired at the base site to allow position averaging of the received signal at the base and to analyze diversity performance at a specific location in each mobile radio environment.

The mobile vehicle was driven in the antenna coverage area within several kilometers around the base site and RSS data was collected over several days of drive testing. The multichannel RSS data collected was stored in data files that contain up to 30 channels of RSS data. The 30 channels consisted of six sector antenna channels and 24 15° beam antenna channels for the 15° multibeam experiment. For the 30° multibeam experiment, only 18 channels need to be

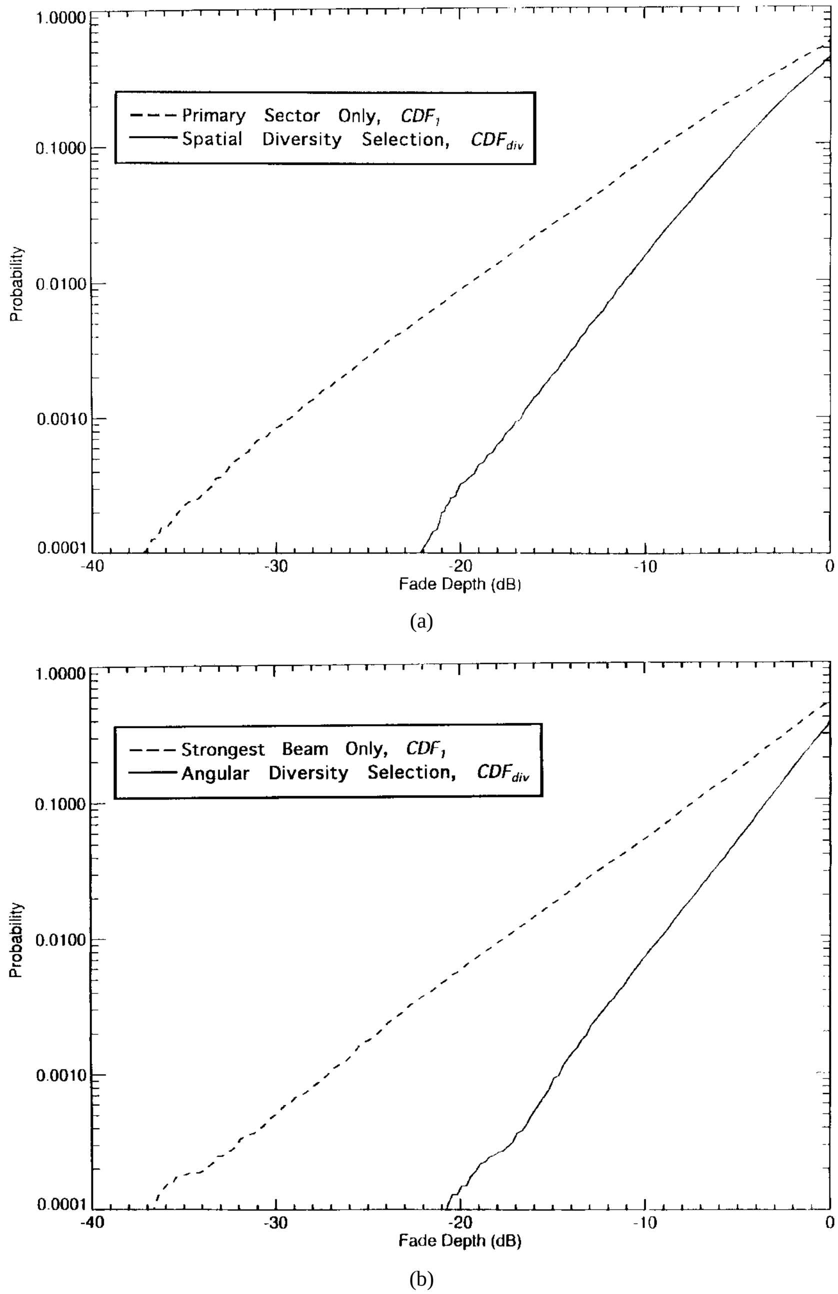


Fig. 4. Fading CDF's in an urban environment using (a) space diversity and (b) angular diversity with 15° multibeams.

connected and recorded—the six sector antenna channels and 12 30° beam antenna channels. These data files typically represented approximately 160 s of vehicle drive time for each of the 30 recorded channels. The duration of the data file was selected to provide a reasonable amount of drive time for analysis and to keep each recorded data file approximately 9 Mb in size for data management purposes. The received signals were sampled at approximately 1 kHz resulting in about 160 000 RSS samples per channel or 4 800 000 samples per data file. Note that all 30 channels were recorded in a data file regardless of whether the 15° or 30° beams were tested.

With this many samples per antenna channel, these data files provide enough fading data for diversity analysis and, therefore, we were able to select specific data files corresponding to a specified location that best represent the mobile radio environment. For example, in Fort Worth, TX, to examine typical rural mobile coverage, we chose drive routes on the north tower face (or X sector), with a unblocked LOS path between the mobile and base site antennas. However, in downtown Seattle, WA, drive routes were selected on the southwest tower face (or Z sector) where the antennas pointed directly into the side of a skyscraper. In this case, the mobile signal was completely nonLOS to the base. Consequently, this resulted in significant scattering of the mobile signal and large changes in the direction of arrival of the base site's received signal.

III. Data Reduction

To evaluate the Rayleigh-fading statistics, we must extract the fast-fading signal from the local mean signal level. A

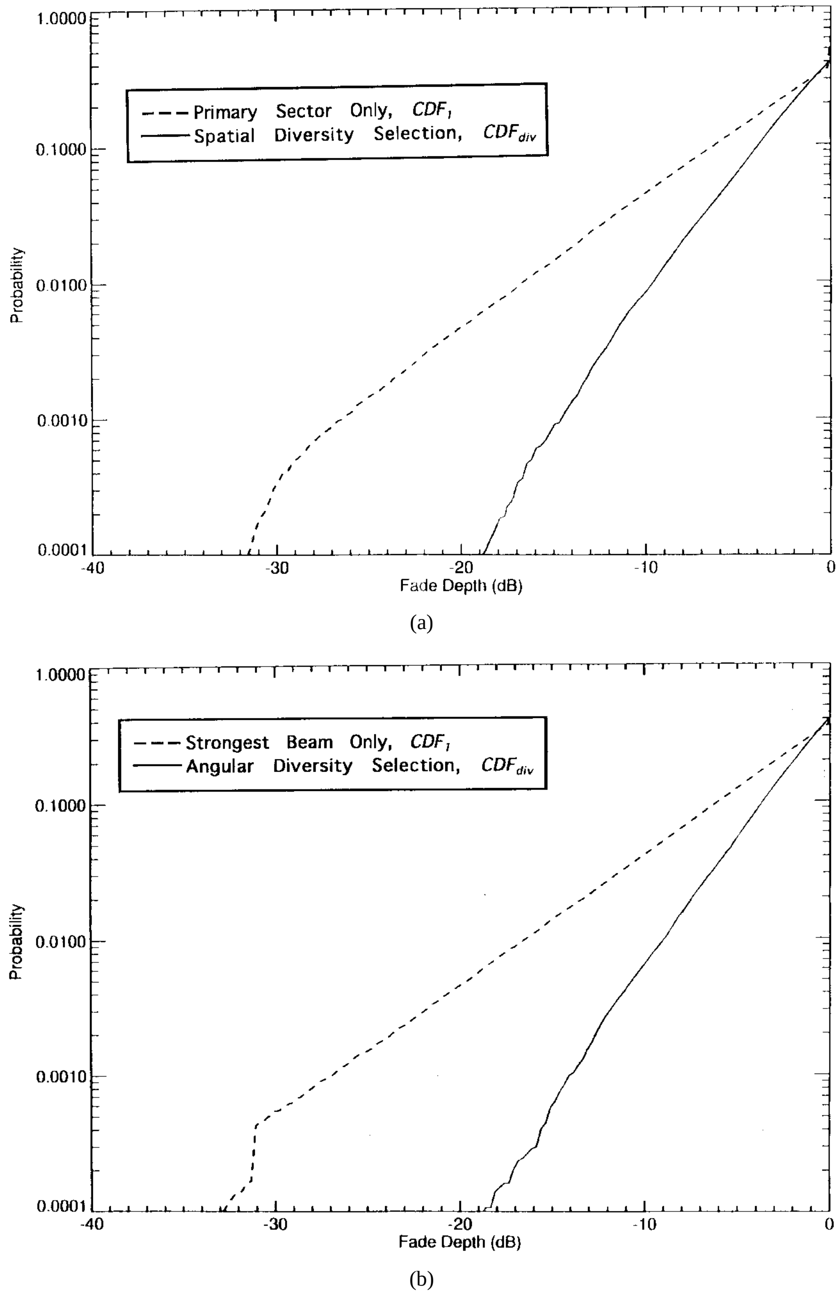


Fig. 5. Fading CDF's in an urban environment using (a) space diversity and (b) angular diversity with 30° multibeams.

fading mobile radio signal results from the multiple rays arriving at the base antenna with different phases and amplitudes producing random fluctuations in the total received signal. This fading has been shown statistically [1], [2] to have a Rayleigh distribution. The received signal $r(t)$ on an antenna channel can be expressed

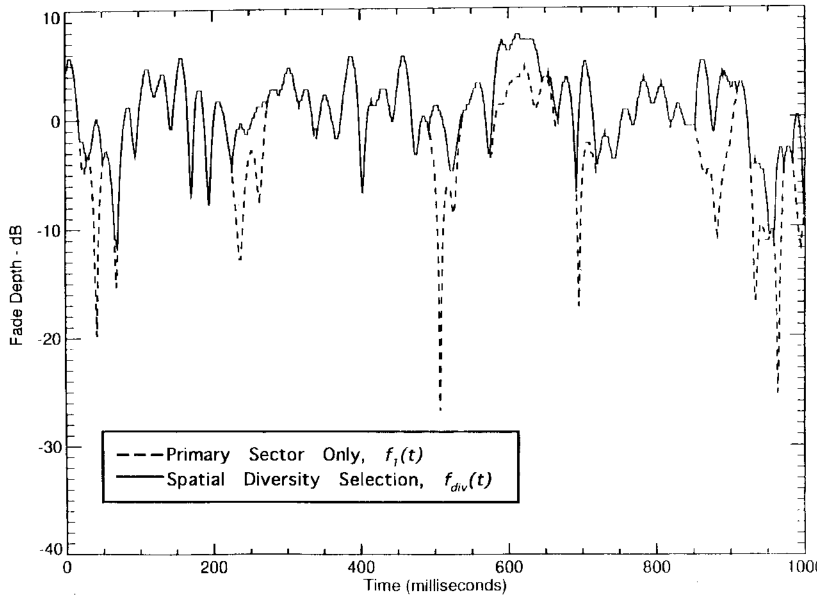
$$r(t) = m(t) + f(t) \tag{1}$$

where $f(t)$ is the fast Rayleigh-fading signal and $m(t)$ is the local mean signal level. The mean signal level is the power received due to the average propagation loss between the mobile and base site and, hence, $m(t)$ decreases as distance between the base and mobile increases. Often modeled as a log-normal signal, $m(t)$ is a slower variation in the received signal than $f(t)$, and, typically, $m(t)$ varies with distance r as a function of $\log(1/r^2)$ in rural environments and $\log(1/r^4)$ in dense urban areas.

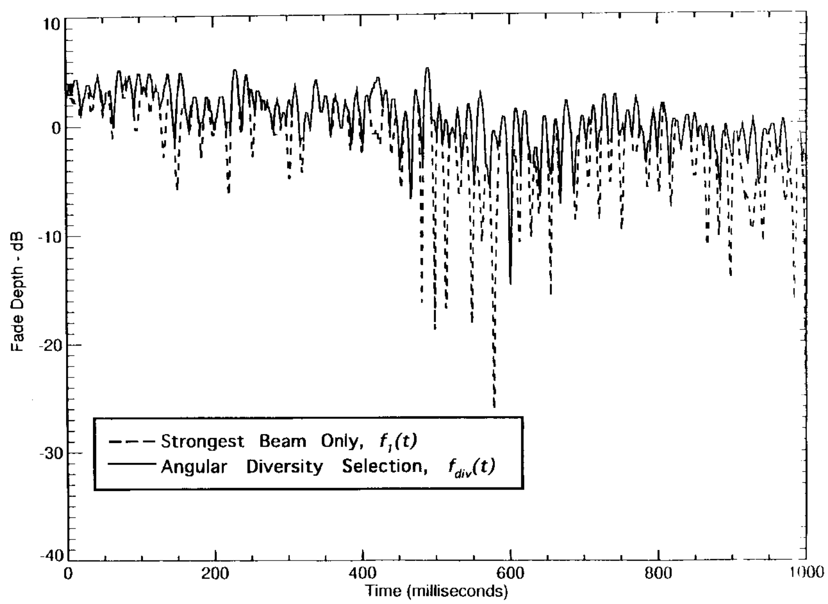
To compute $m(t)$, $r(t)$ must be averaged over a distance of 40 wavelengths [12], which is approximately 15 m (50 ft) at 850 MHz. Since the distance traveled depends on vehicle speed, the mean signal level can be computed as

$$m(t) = \frac{1}{\Delta t} \int r(t)\, dt \bigg|_{\Delta t = (40\lambda/v)} \tag{2}$$

where v is the vehicle speed and Δt is the time required to travel 40 wavelengths at that velocity. Note that the averaging period Δt varies with vehicle speed and, hence, the averaging period changes over time. This is important because if the averaging period is too short, at slow speeds the mean signal $m(t)$ will contain large fluctuations due to fading. Conversely,



(a)



(b)

Fig. 6. Rayleigh-fading in an urban environment using (a) 90° sector antenna and (b) 30° multibeam antenna.

at high speeds, if the averaging period is too long, fluctuations in $m(t)$ due to propagation loss over varying terrain will be averaged out. Using the appropriate averaging period with vehicle speed provides an accurate estimate of $m(t)$ over time. By subtracting $m(t)$ from $r(t)$ we obtain the Rayleigh-fading signal $f(t)$

$$f(t) = r(t) - \frac{1}{\Delta t} \int r(t)\, dt \Big|_{\Delta t = (40\lambda/v)}. \tag{3}$$

With the mean signal removed, the fast-fading signal varies about a zero reference and the probability of fading outages (in decibels relative to the mean RSS) can be independently examined. Typically, this is plotted as a cumulative distribution function (CDF) of the fading signal $f(t)$ such as those figures presented in Section V.

IV. Antenna Selection Diversity and Diversity Gain

Cellular systems employ receive diversity at the base site to reduce signal outages due to fast fading. A diversity receiver can be switched between two antenna channels that have uncorrelated fast-fading signals in order to obtain the maximum signal output. Two such antenna channels with receive signals $r_1(t)$ and $r_2(t)$, each containing fast-fading components given by $f_1(t)$ and $f_2(t)$, form the output of a selection diversity receiver $r_{\text{div}}(t)$ expressed as

$$r_{\text{div}}(t) = \text{Maximum}\{r_1(t), r_2(t)\} \tag{4}$$

where $r_{\text{div}}(t)$ is the greater of $r_1(t)$ and $r_2(t)$. In space diversity the mean signals for the two antenna channels are $m_1(t)$ and $m_2(t)$. With angle diversity, there is a separate

TABLE I
ANGLE AND SPACE DIVERSITY GAIN COMPARISONS IN (a) URBAN AND (b) RURAL MOBILE RADIO ENVIRONMENTS

Urban Seattle Tests	15° Multibeam - Fig. 4	30° Multibeam - Fig. 5
Angle $G_{div}(1\%)$	8.5 dB	7.5 dB
Space $G_{div}(1\%)$	8.0 dB	7.0 dB
Angle $G_{div}(10\%)$	4.0 dB	2.5 dB
Space $G_{div}(10\%)$	4.0 dB	2.5 dB

(a)

Rural Ft. Worth Tests	15° Multibeam - Fig. 7	30° Multibeam - Fig. 8
Angle $G_{div}(1\%)$	0 dB	1.0 dB
Space $G_{div}(1\%)$	2.5 dB	5.5 dB
Angle $G_{div}(10\%)$	0 dB	0 dB
Space $G_{div}(10\%)$	1.0 dB	2.0 dB

(b)

mean signal $m_i(t)$ for each antenna beam, where i is the antenna beam number. For example, i ranges from 1 to 12 for the 12 30° beams and from 1 to 24 for the 24 15° beams. To obtain the angular diverse receive signals $r_1(t)$ and $r_2(t)$, we need to determine the strongest two mean received signals $m_1(t)$ and $m_2(t)$ from the available antenna beams. Note that for each pair of mean signal averages $m_1(t)$ and $m_2(t)$, there will be a corresponding pair of $r_1(t)$ and $r_2(t)$ that can come from any pair of the available antenna beams.

With $r_{\text{div}}(t)$ defined, the fast-fading signal component $f_{\text{div}}(t)$ can be expressed as

$$f_{\text{div}}(t) = \begin{cases} f_1(t); r_1(t) > r_2(t) \\ f_2(t); r_1(t) < r_2(t). \end{cases} \qquad (5)$$

In angle diversity, $m_1(t)$ and $m_2(t)$ are not generally equal as is the case with space diversity. This is because with angle diversity, the antenna beam coverages of the two diversity antenna channels are not identical or pointed in the same direction. In a base-station receiver, diversity selection is made between the absolute power levels $r_1(t)$ and $r_2(t)$ with no knowledge of $m_1(t)$ and $m_2(t)$. Since the fading can be much greater than the difference between $m_1(t)$ and $m_2(t)$, $f_{\text{div}}(t)$ may contain fast-fading signal components of $r_1(t)$ (i.e., $f_1(t)$) even though the mean signal $m_2(t)$ is greater than $m_1(t)$.

Diversity is effective when two (or more) antenna terminals produce mobile received signal strengths that are uncorrelated with regard to mobile Rayleigh-fading, but whose local average strengths $m_1(t)$ and $m_2(t)$ are about equal. If the two mean signals are unequal or unbalanced, say $m_1(t) > m_2(t)$, then diversity performance degrades because the received signals being compared for selection diversity $r_1(t)$ and $r_2(t)$ are at different references. This imbalance causes the one channel with higher mean power $r_1(t)$ to be selected more often because it needs to fade by the difference $m_1(t) - m_2(t)$ before $r_1(t)$'s absolute power drops below $r_2(t)$. This paper demonstrates that this possible imbalance in $m_1(t)$ and $m_2(t)$ impacts angle diversity performance in rural or LOS cellular environments. Due to the multiple angles of arrival of the received signal in urban environments (i.e., scattering of the mobile signal), this imbalance will be small and angle diversity should be effective in mitigating fading. However, in rural environments if the received signal has a unblocked LOS path, the difference between $m_1(t)$ and $m_2(t)$ will be significant and, consequently, angle diversity should be less effective.

Diversity gain performance is obtained by comparing the fading CDF of $f_1(t)$ on a single antenna channel at a specified probability to the fading CDF of $f_{\text{div}}(t)$, the fast fading associated with the selection diversity receiver output $r_{\text{div}}(t)$. In space diversity, we use the $f_1(t)$ of the primary sector antenna (X, Y, or Z) in which the mobile resides to obtain the fading CDF of a single antenna channel. However, in angle diversity, $f_1(t)$ comes from the fast-fading components of the stongest beam available, $m_1(t)$. Note that over time, $m_1(t)$ and, hence, $f_1(t)$ may come from different antenna beams as the maximum mobile received signal changes its direction of arrival at the base site.

To make the comparison of the CDF's of $f_1(t)$ and $f_{\text{div}}(t)$, we express the CDF of $f_1(t)$ as

$$\text{CDF}_1 = P[X_1 \le x_o] \qquad (6)$$

where X_1 is the fade depths of $f_1(t)$, the random variable of CDF_1. We express the CDF of $f_{\text{div}}(t)$ as

$$\text{CDF}_{\text{div}} = p[X_{\text{div}} \le x_o] \qquad (7)$$

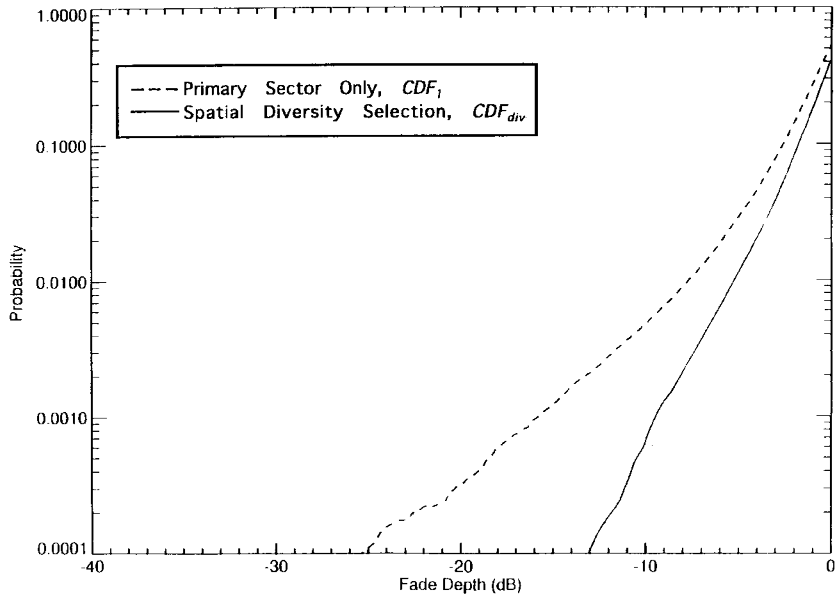
where X_{div} is the fade depths of $f_{\text{div}}(t)$, the random variable of CDF_{div}. The diversity gain $G_{\text{div}}(p_o)$ at the specified probability p_o is expressed as

$$G_{\text{div}}(p_o) = X_{\text{div}}[P = p_o] - X_1[P = p_o]\ (\text{dB}) \qquad (8)$$

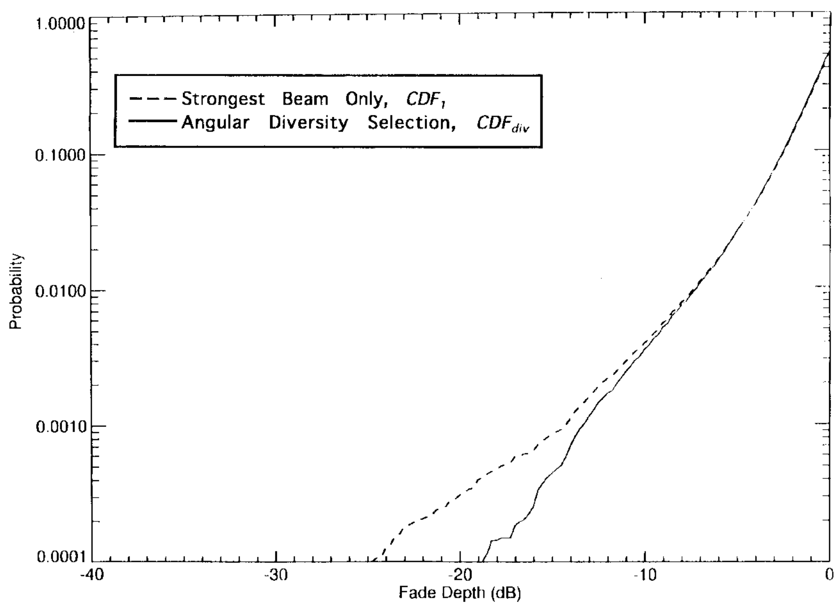
where $X_{\text{div}}[P = p_o]$ is the fade-depth value x_o at the specified probability p_o for the CDF of $f_{\text{div}}(t)$ and $X_1[P = p_o]$ is the fade-depth value x_o at the same probability p_o for the CDF of $f_1(t)$. Note that the specified probability p_o is constant when comparing the two CDF's and that the resulting diversity gain is the difference of the two fade-depth random variables X_1 and X_{div} in decibels. Depending on the probability p_o specified, the resulting diversity gain changes. Typically, diversity gain is evaluated at $p_o = 0.01$ or $p_o = 0.1$ to obtain the fade-depth improvement at 1 or 10% of the total fading outages.

The computation of diversity gain is identical for both space and angle diversity once $r_1(t)$ and $r_2(t)$ are specified for both cases. For the spatially diverse sector antennas, we used the two antenna channels from the sector (X, Y, or Z) in which the mobile was located. The space-diversity antenna responses of the sector antennas $r_1(t)$ and $r_2(t)$ can be compared using (5) to obtain $f_{\text{div}}(t)$. Once $f_{\text{div}}(t)$ is known, the cummulative distribution functions CDF_{div} and CDF_1 can be obtained and the space-diversity gain computed using (8).

In the case of the angle diversity, the primary selected channel $r_1(t)$ was the ith antenna beam (of the 12 or 24 available) that had the greatest average power, which we shall denote as $m_1(t)$. The second angular-diverse antenna beam $r_2(t)$ was selected by choosing the next beam with the second strongest mean signal denoted as $m_2(t)$. Note that with angle



(a)



(b)

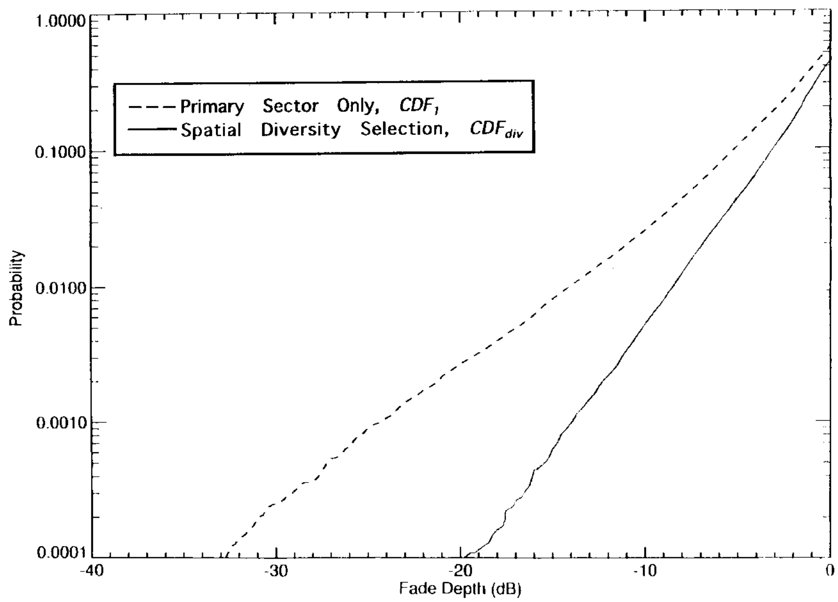
Fig. 7. Fading CDF's in a rural environment using (a) space diversity and (b) angular diversity with 15° multibeams.

diversity, the antenna beams with the strongest two average signal levels from all 12 (or 24) available beams are used to obtain the appropriate $r_1(t)$ and $r_2(t)$. Hence, for each pair of mean signal averages $m_1(t)$ and $m_2(t)$ there will be a corresponding pair of $r_1(t)$ and $r_2(t)$, which can come from any pair of the available antenna beams depending on which beams had the strongest mean signal levels. Once $r_1(t)$ and $r_2(t)$ are known for the angle-diversity configuration, we can obtain $f_{\text{div}}(t)$ and, consequently, CDF_{div} and CDF_1 to compute the angle diversity gain using (8).

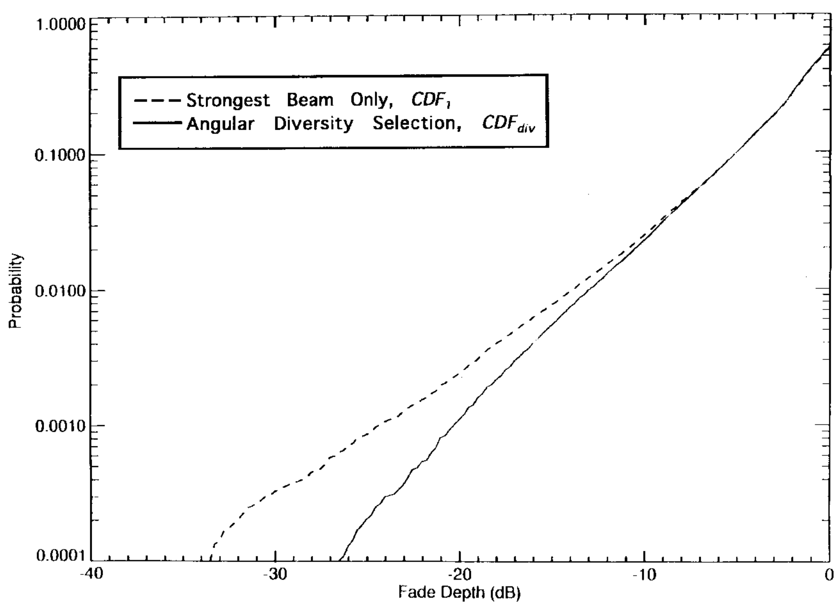
V. Experimental Results

Figs. 4 and 5 depict the fading CDF's for space diversity and angular diversity in a dense urban environment. Fig. 4 compares space diversity, shown in Fig. 4(a), and angular diversity using the 15° beams shown in Fig. 4(b). Similarly, Fig. 5(a) and (b) shows the comparison of space diverity with angle diversity using 30° beams. Note that in both Figs. 4 and 5, the dashed line represents the CDF of $f_1(t)$, CDF_1 and the solid line represents the CDF of $f_{\text{div}}(t)$, CDF_{div}. Fig. 6 gives two examples of the fading signals and demonstrates, temporally, the effect of diversity on mitigating fading. Fig. 6(a) depicts the fading process on two space-diversity antenna channels and Fig. 6(b) shows the fading on two angular-diverse antenna channels. In both plots, the solid line is the output of the diversity receiver and the dashed lines are those fades that were eliminated from the primary antenna channel $f_1(t)$ by employing selection diversity.

Notice in the urban environment of Seattle, WA, the fading CDF's of a single channel CDF_1 (shown as dashed lines in



(a)



(b)

Fig. 8. Fading CDF's in a rural environment using (a) space diversity and (b) angular diversity with 30° multibeams.

Figs. 4 and 5), is approximately Rayleigh distributed where 1% of the fades exceed -20 dB. With diversity implemented, we see that $\mathrm{CDF}_{\mathrm{div}}$ is to the right of CDF_1, indicating that the probability of deep fades is reduced when compared to CDF_1. Recall from (8), the diversity gain is the difference between the two CDF's abcissas at a specified probability. For example, in Fig. 4(a), 1% of the fades exceeded -19 dB on a single channel, but with space diversity, only 1% of the fades were below -11 dB. Therefore, the space-diversity gain $G_{\mathrm{div}}(1\%)$ is 8 dB. As mentioned previously, depending on the probability specified, the diversity gain changes. For example, in Fig. 4(a), at 10% probability, the space-diversity gain $G_{\mathrm{div}}(10\%)$ drops to about 4 dB. Similar computations can be made with the other CDF's of Fig. 4(b) and Fig. 5(a) and (b) to determine the angle and space-diversity performance. Those results are tabulated in Table I(a)

Figs. 7 and 8 give the fading CDF's for angle and space diversity in the rural flat terrain of Fort Worth, TX. Fig. 7 compares space diversity [shown in Fig. 7(a)] and angular diversity using the 15° beams shown in Fig. 7(b). Similarly, Fig. 8(a) and (b) show the comparison of space diversity with angle diversity using 30° beams. Fig. 9 gives two more time history examples of the fading signals and demonstrates the negligible effect of diversity on mitigating fading in rural environments. Fig. 9(a) depicts the fading process on two space-diversity antenna channels and Fig. 9(b) shows the fading on two angular diverse antenna channels. In both cases, notice how infrequently deep fades occur and how little

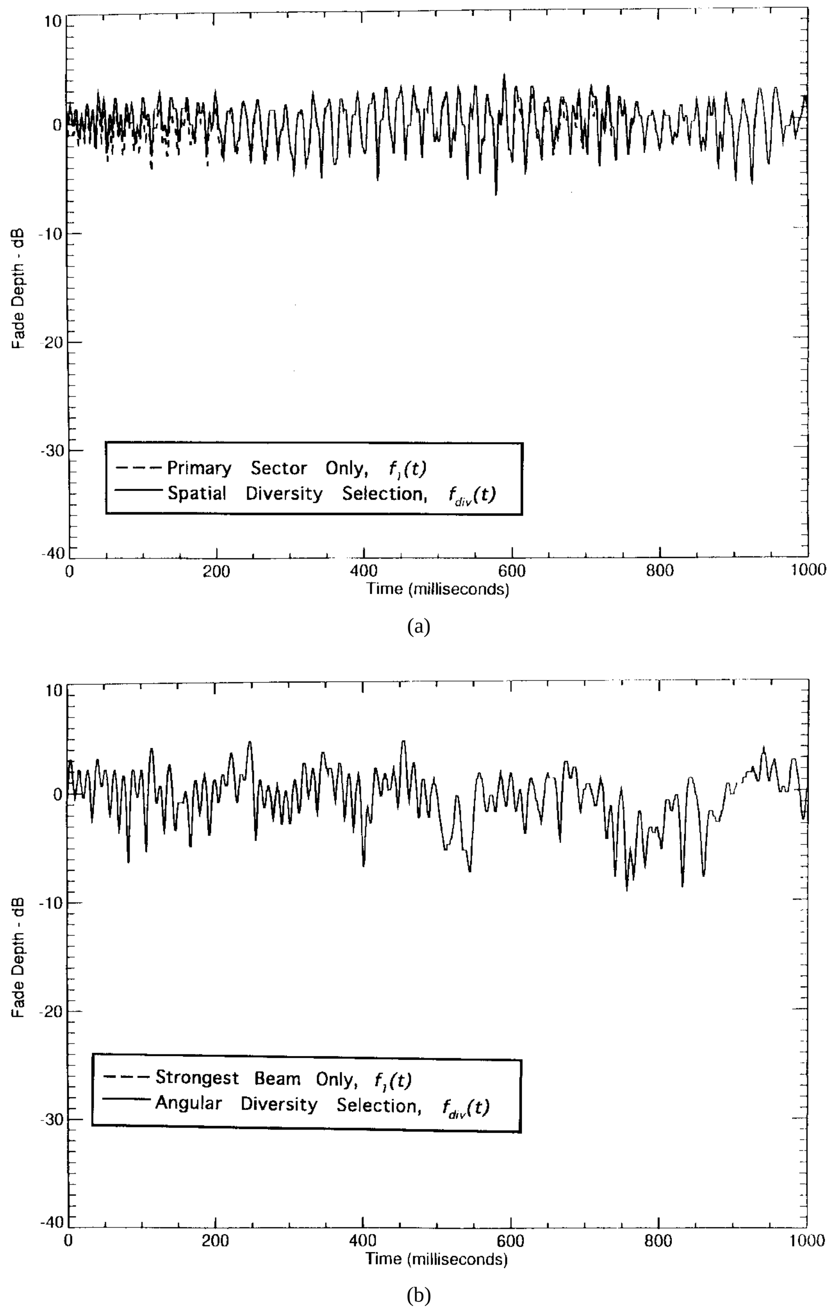


Fig. 9. Rayleigh-fading in a rural environment using (a) 90° sector antenna and (b) 30° multibeam antenna.

diversity improves fading outages. Because of the direct LOS path, the fading CDF of $f_1(t)$, CDF_1 has moved significantly to the right, indicating that there are very few deep fades (exceeding -10 dB). The fading CDF's of CDF_1 in Figs. 7 and 8 more closely resembles a Rician distribution as opposed to the Rayleigh distribution seen in the CDF's Figs. 4 and 5.

The space and angle diversity gains for the urban and rural tests are tabulated in Table I. The urban results from Figs. 4 and 5 are tabulated in Table I(a) and the rural diversity performance is given in Table I(b). For the urban tests in downtown Seattle, the diversity gain of the 15° and 30° multibeams using angular diversity seemed to compare closely with traditional sector antennas employing space diversity, with the angular diversity performance being slightly higher than space diversity at the 1% probability level. However, in the rural tests, the overall improvement provided by angle and space diversity was much less. Typically, in the rural setting, the fade probabilities improved 1–2 dB for space diversity; virtually no improvement was obtained using angle diversity.

As mentioned earlier in this section, the possible imbalance in $m_1(t)$ and $m_2(t)$ for angular diverse antennas impacts angle diversity performance in rural or LOS cellular environments. This power imbalance on diversity channels can be examined by plotting the CDF of the difference between $m_1(t)$ and $m_2(t)$. Such CDF's in urban and rural environments are shown Figs. 10 and 11, respectively. Recall that in the high-scattering

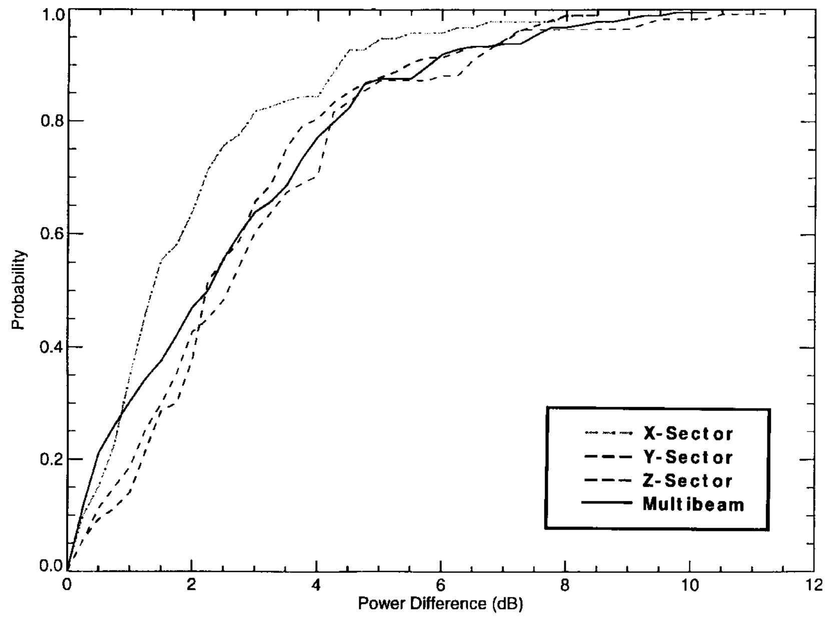


Fig. 10. CDF of mean-power differences on angle- and space-diversity channels in an urban environment.

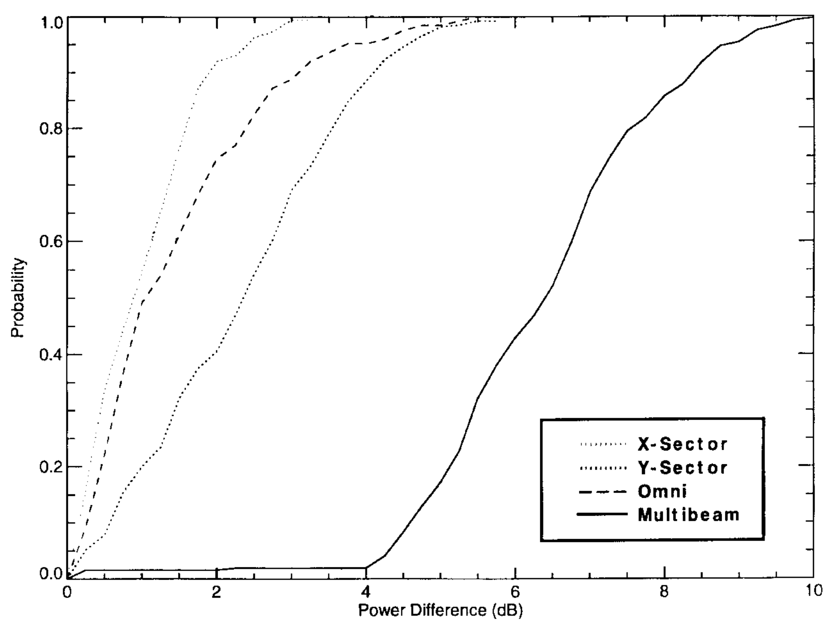


Fig. 11. CDF of mean-power differences on angle- and space-diversity channels in an rural environment.

urban environment, we located the mobile in the Z sector (or Z-tower face). For this sector, the power imbalance at the 50th percentile of Fig. 10 is less than 2 dB for both the Z-sector antennas and the multibeams. This suggest that there is significant scattering of the mobile signal as to produce little or no imbalance in $m_1(t)$ and $m_2(t)$. However, in a rural direct LOS-type environment, the power imbalance on the multibeams at the 50th percentile of Fig. 11 was over 6 dB, but the imbalance on the X-sector antennas (the sector in which the mobile resided for the rural tests) was only 1 dB. The larger imbalance on the angular diversity channels reduced the angle diversity gain significantly. This imbalance is to be expected in a LOS situation when narrower angular beams pointed in different directions are used. Large imbalances were not seen with the space-diversity antennas since both antennas have identical coverage in a sector.

VI. Conclusions

Results for angle and space diversity were compared in different mobile radio environments. The results indicate that angle diversity compares closely with traditional space diversity in a complex scattering or dense urban location. However, for rural applications, angle diversity does not work as effectively as space diversity. The main reason for the degraded angle-diversity performance in rural locations is a large mean-signal imbalance on the diversity channels. This difference in mean signal reduces the selection diversity gain on the order of that imbalance. Angle and space diversity reduce fading outages in an urban mobile radio environment where the propagation channel experiences Rayleigh-fading. However, less improvement is obtained in rural environments where the propagation channel is better described by Rician fading. This research suggests that angle diversity can be considered for combating fading in urban cellular and PCS deployments.

ACKNOWLEDGMENT

The author would like to thank D. O. Reudink, D. Jones, M. Harrison, J. O'Conner, D. Ellingsworth, and P. Zencak for their efforts in organizing this experiment and their time devoted in the field. Hundreds of hours were spent on setting up antennas, equipping vehicles, acquiring data, driving, etc., in the various test locations. This paper would not be possible without their efforts.

REFERENCES

[1] R. Steele, *Mobile Radio Communications.* Piscataway, NJ: IEEE Press, 1995, ch. 2.
[2] W. C. Jakes, *Microwave Mobile Communications.* Piscataway, NJ: IEEE Press, 1993, ch. 2.
[3] G. D. Alley, C. H. Bianchi, and W. A. Robinson, "Angle diversity and space diversity experiments on the Salton/Brawley Hop," *IEEE Trans. Commun.*, vol. 40, pp. 440–454, Feb. 1992.
[4] D. Di Zenobio, E. Russo, and S. Candeo, "Angle diversity performance of a line-of-sight path using a dual beam dish antenna," in *Proc. 7th Int. Conf. Antennas Propagat.*, York, U.K., Apr. 1991, pp. 306–309.
[5] D. Di Zenobio, G. Santella, S. Candeo, and D. Mandich, "Angle and space diversity: experimental comparison," in *Proc. IEEE Global Telecommun. Conf. GLOBECOM92*, Orlando, FL, Dec. 1992, vol. 3, pp. 1851–1857.
[6] B. Danielsson, "Measured improvements using angle and space diversity on a terrestrial radio link," in *Proc. 4th Eur. Conf. Radio Relay Syst.*, Edinburgh, U.K., Oct. 1993, pp. 215–220.
[7] L. Ordano, "A prediction method for angle diversity improvement on digital radio links." in *Proc. 7th Int. Conf. Antennas Propagat.*, York, U.K., Apr. 1991, pp. 302–305.
[8] M. Glauner, "Equivalence relations between angle diversity and other diversity methods. Analytical model and practical results," in *Proc. 4th Eur. Conf. Radio Relay Syst.*, Edinburgh, U.K., Oct. 1993, pp. 261–266.
[9] M. Hamer and M. Butcher, "Experimental vehicular angle diversity antenna using mutual coupling," in *Proc. IEEE Int. Antenna Propagat. Symp.*, Chicago, IL, July 1992, pp. 1089–1092.
[10] A. R. Webster and T. S. Merritt, "Multipath angles-of-arrival on a terrestrial microwave link," *IEEE Trans. Commun.*, vol. 38, pp. 25–30, Jan. 1990.
[11] R. E. Collin, *Antennas and Radiowave Propagation.* New York: McGraw-Hill, 1995, pp. 141–143.
[12] W. Y. C. Lee, "Estimate of local average power of a mobile radio signal," *IEEE Trans. Veh. Technol.*, vol. 34, pp. 22–27, Feb. 1985.

Patrick L. Perini (M'86) was born in Syracuse, NY, on July 18 1964. He received the B.S. degree in electrical engineering from Syracuse University, Syracuse, NY, and the M.S. and Ph.D. degrees in electrical engineering from the University of Colorado at Boulder (UCB), in 1985, 1989, and 1993, respectively.

From 1985 to 1993, he worked as a Member of the Technical Staff at NASA's Jet Propulsion Laboratory (JPL), Pasadena, CA, developing the antenna subsystem for the shuttle imaging radar (SIR-C). While at JPL, he worked on the develpoment of wide-band microstrip antennas for spaceborne radars and developed analog and digital electronics used to qualify RF transmission lines for space flight. In 1993 he joined the technical staff at U.S. West Advanced Technologies, Boulder, CO, where his research efforts have been focused on antenna technology for wireless communication systems. Currently, he is a Distinguished Member of the Technical Staff and his research interests include intelligent antenna systems for personal communication systems (PCS) and cellular telephony, electromagnetic (EM) propagation modeling, antenna diversity techniques, microwave technology, and code division multiple access (CDMA) link analysis.

Christopher L. Holloway (S'86–M'92) was born in Chattanooga, TN, on March 26, 1962. He received the B.S. degree from the University of Tennessee at Chattanooga and the M.S. and Ph.D. degrees (both in electrical engineering) from the University of Colorado at Boulder, in 1986, 1988, and 1992, respectively.

During 1992, he was a Research Scientist with ElectroMagnetic Applications, Inc., in Lakewood, CO. His responsibilities included theoretical analysis and finite-difference time-domain (FDTD) modeling of various electromagnetic problems. From the fall of 1992 to 1994 he was with the National Center for Atmospheric Research (NCAR) in Boulder, CO. While at NCAR his duties included wave-propagation modeling, signal-processing studies, and radar systems design. Since 1994 he has been with the Institute for Telecommunication Sciences (ITS) at the U.S. Department of Commerce, Boulder, CO, where he is involved in wave-propagation studies. His research interests include electromagnetic field theory, wave propagtion, guided-wave structures, remote sensing, numerical methods, and electromagnetic compatibility/electromagnetic interference (EMC/EMI) issues.

Dr. Holloway is a member of Commission A of the International Union of Radio Science and is an Associate Editor on propagation for the IEEE TRANSACTIONS ON ELECTROMAGNETIC COMPATIBILITY.