CHAPTER 8
SPATIAL, POLARIZATION, AND PATTERN DIVERSITY FOR WIRELESS HANDHELD TERMINALS

8.1 Introduction

This chapter examines the diversity dimensions of antenna configurations that affect performance in handheld radios. Experiments were conducted in Ricean fading line-of-sight and obstructed outdoor and indoor multipath channels using spatial, polarization, and pattern diversity. Antenna separation, polarization, and pattern are varied independently to the extent possible. Envelope correlation, power imbalance, and diversity gain were calculated from the measurements. Differing antenna polarizations or pattern distortions result in power imbalance between diversity branches. For a given cross-correlation, diversity gain decreases as power imbalance increases. Diversity gain allows a direct comparison of the performance that can be achieved with each configuration. A diversity gain of 7 to 9 dB at the 99% reliability level was achieved in non line-of-sight channels for all diversity configurations even with very small antenna spacings. The use of polarization diversity also reduced polarization mismatches, improving SNR by up to 12 dB even in line-of-sight channels.

Antenna diversity for land-mobile radio base stations has been proven to be very effective. In fact, spatial diversity with receive antennas spaced typically ten or more wavelengths apart on cellular telephone towers is in widespread use. Base station spatial diversity is discussed by Lee [8.1]. Polarization diversity has been found to be nearly as effective as spatial diversity for base stations [8.2]-[8.4], and provides a great space and cost savings. Polarization diversity also compensates for polarization mismatch due to random handset orientation [8.5]. Pattern diversity using multiple directional beams has also been investigated for use at base stations that have switched-beam smart antennas [8.6].

Spatial diversity for reception uses two or more antennas separated in space. Transmit diversity is also effective, but systems are often uplink-limited and link improvements most needed for the receive side of the base station. In multipath propagation conditions, as encountered with a blocked or shadowed direct line-of-sight (LOS) path, each receive antenna experiences a different fading environment. Thus, it is highly likely that if one antenna is in a deep fade, then the other one is not and provides sufficient signal.

Base stations require wide antenna spacings for proper diversity operation because the multipath arrival is over a narrow angle spread [8.1]. However, as shown in [8.7], under wide multipath angle spread conditions diversity spacing can be small. This occurs in outdoor urban environments and for indoor operation of mobile/personal terminals.

This chapter presents results from a major measurement campaign that demonstrated the effectiveness of spatial diversity for use in handsets and investigated other fundamental mechanisms that contribute to diversity gain. It was found that antenna spacings as small as one-tenth wavelength provide up to 8 dB diversity gain at a 1% outage level. Similar large gains for polarization and pattern diversity with small antenna spacings were also observed. Measurements including operator effects showed a diversity gain of over 8 dB using antennas spaced 0.25 wavelength apart with the operator's head next to the antennas. The results of this investigation can be used to design effective diversity antennas for handheld radios.

8.2 Diversity Principles

We begin with a review of diversity principles. Discussion is confined to receive diversity, although transmit diversity can have similar effects. Diversity antennas provide two major benefits. First, reliability is improved in multipath channels where interference from reflected signals causes fading of the received signal. The fade level experienced on average for a given outage probability (percent down time) is decreased through diversity. Systems that use diversity combining can provide a 10 dB or greater diversity gain (to be defined below) for the worst 1% of cases. Second, the overall average received signal power is increased. Systems that use polarization or angle diversity automatically match the antenna characteristics to the received signal and increase the efficiency of the radio link. These gains can be dramatic. A radio without polarization diversity can easily experience a 10 to 20 dB decrease in mean received signal power due to polarization mismatch. A simple polarization diversity system can provide at least half the best-case received signal power for even the worst polarization mismatch.

The use of diversity antennas results in improvements in system performance over that of a system that does not use diversity antennas. Diversity gains from handheld radios that use diversity antennas permit the use of lower transmit power for a given level of reliability. Thus, diversity reduces interference to and from other users, and reduces the probability that a hostile party will intercept the signals. Battery life is increased in peer-to-peer handheld systems. The outputs from diversity antennas can be selected or combined in several ways to optimize the received signal power or SNR. These techniques include maximal ratio combining, equal gain combining, selection diversity, and switched diversity; these methods are described in Chapter 3, and in more detail in [8.8]. In this investigation maximal ratio combining and selection diversity are considered. The two techniques do not differ greatly in performance, with maximal ratio combining providing about 1.5 dB higher diversity gain at the 1% cumulative probability (99% reliability) level. Adaptive beamforming algorithms can also provide diversity gain, in addition to rejecting interfering signals [8.9].

In general, multiple diversity dimensions can be exploited dynamically in receivers. The diversity dimensions that are available are (also see Fig. 8-1):

Spatial – multiple antenna elements occupy separate locations on the radio

Polarization – the antenna(s) provide dual orthogonal polarizations

Pattern or Angle – directional antennas discriminate over angle space

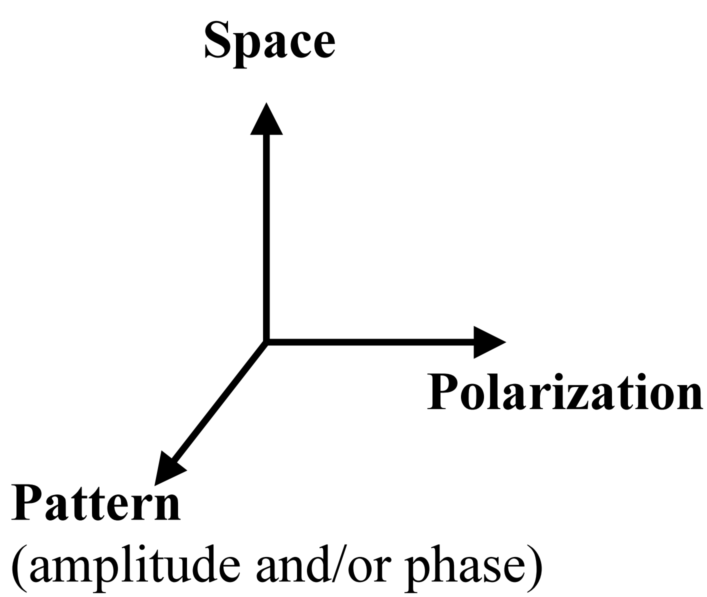


Figure 8-1. Three "dimensions" of antenna diversity

Diversity combining techniques do effectively steer beams when used in spatial diversity configurations, and should provide performance similar to angle diversity. However, when directional patterns are used with selection diversity, this can differ significantly from selection between two nominally omnidirectional patterns. It is desirable to understand the effects of varying each dimension but in practice it is difficult to vary all three dimensions independently.

Antenna diversity is most effective in flat fading channels where the fading is correlated across the signal bandwidth. Flat fading is experienced in two situations: in narrowband system channels with propagation distances of up to several km, and in wideband systems over indoor and pico- or microcellular channels with small delay spreads. Equalizers or RAKE receivers employed in wideband radios cannot mitigate flat fading with a single antenna [8.10].

Diversity gain quantifies the improvement in SNR of a received signal that is obtained using signals from different receiver branches. Diversity gain permits a direct comparison of improvement offered by multiple antenna sensors compared to a single one. The diversity gain for a given cumulative probability p is given by

$$G_{div}(p) = \gamma_{div}(p) - \gamma_1(p) \tag{8.1}$$

where γ_{div} is the SNR with diversity and γ_1 is the SNR of a single branch without diversity combining. Diversity gain is the improvement in signal level or SNR, due to diversity combining, for a given level of cumulative probability or reliability.

Diversity gain is maximized if the correlation of the envelopes of the signals received by each receiver branch is zero (or negative, but large negative correlations are atypical), and if the branch powers (and equivalently the SNRs of the branches) are perfectly balanced. Diversity gain decreases with increasing branch correlation and power imbalance. [8.3], [8.11] The relationship between diversity gain, branch correlation, and power balance was developed based on experimental data by Turkmani [8.3]. Analytical expressions for diversity gain of various combining techniques in Rayleigh fading channels as functions of branch correlation and power balance have been derived by Dietze [8.11] and are used in this paper.

The effect of power imbalance is often ignored but can be very significant, especially in the case of polarization and pattern diversity. Theoretical expressions for diversity gain have been developed for Rayleigh fading channels. Many channels have a line-of-sight or a dominant reflected or diffracted component and are better characterized by a Ricean distribution. In these channels, fading is less severe and the potential diversity gain is lower than in Rayleigh fading channels.

Diversity gain is greatest if the envelope cross-correlation between branches is low. In spatial diversity systems, the correlation between the envelopes is a function of the spacing between the antennas. The relative phases of received multipath signals incident from different directions change with the position of the receiving antenna so that spatially separated antennas experience partially correlated fading. Correlation tends to decrease as antenna spacing increases. Clarke [8.7] derived the following relationship between envelope correlation and antenna separation, assuming multipath with a uniform angle of arrival distribution in azimuth and antennas with omnidirectional patterns.

$$\rho_e \cong J_0^2\left(\frac{2\pi d}{\lambda}\right) \tag{8.2}$$

where J_0 is a Bessel function of the first kind with order zero, d is the antenna spacing, and λ is the wavelength. The correlation between the envelopes of signals received by two antennas is also decreased if the patterns of each antenna are different. In this case the relative amplitudes of the incident multipath signals are different at each antenna, even if the antennas are collocated. The patterns of closely spaced antennas that are omnidirectional in free space are distorted due to mutual coupling. The effects of mutual coupling on envelope correlation were investigated Vaughan and Scott [8.12], who showed that envelope correlations for closely spaced monopoles were much lower than predicted by (8.2).

Various forms of diversity have been considered for use at the mobile handset [8.13] - [8.26]. The antenna systems include two or more elements, and some combination of spatial, polarization, and pattern diversity is implemented with the antenna array system. Antenna elements that have been used include whip antennas, planar inverted F-antennas (PIFA), and microstrip patch antennas. Measurements show that the elements can be very closely spaced and still achieve low correlation coefficients between the diversity branches. For three-branch systems, gains of up to 13 dB over a single element system have been reported by Mano [8.18]. So far, however, little research has been reported that attempts to isolate the effects of spatial, polarization, and pattern diversity in hand-held applications. These diversity approaches were studied individually to gain insight into how they can be combined effectively. Experiments were performed to evaluate the effects of antenna spacing, pattern, and polarization on diversity performance. The results are useful in guiding how operational systems can be configured.

8.3. Experimental Configuration

Experiments were performed using the handheld antenna array testbed (HAAT) to evaluate the performance of various diversity systems under tightly controlled conditions as well as in more typical operational scenarios. The HAAT is designed for maximum portability and flexibility and optimized for the purpose of taking measurements. The system is used to evaluate the performance of alternative antenna configurations and combining techniques.

8.3.1 Handheld antenna array testbed (HAAT)

The HAAT, described in Chapter 6, consists of transmitters, a positioner for the receiver, a receiving system, and a data processing system. The two-channel receiver described in Section 6.5 was used for the experiments discussed here. Figure 8-2 is a high level diagram showing the components and outputs of the testbed. The operating frequency of 2.05 GHz was selected for relevance to PCS and PCN bands. The transmitters typically operate from a fixed position but are transportable and are powered by batteries for use in the field. The portable positioning system is used to move the receiver for controlled measurements. It consists of a non-metallic track approximately 3 m in length. The useable length of the track is about 2.8 m (approximately 19 wavelengths at 2.05 GHz). The receiver unit is mounted on a carriage that is moved along the track at a constant speed of 0.115 m/s, using a stepper motor, while measurements are conducted. The track is mounted on an adjustable tripod to allow use on any terrain. An electronic level is used to adjust the tripod to level the track. Transmitter and receiver heights were approximately 1.5m. Data are collected using the portable receiver system and analyzed off line to allow comparison of different combining techniques. In the non-interference scenarios reported in this paper the performance measure is diversity gain and in scenarios where adaptive beamforming techniques used to reject interfering signals, the performance measure is SINR improvement vs. a single antenna.

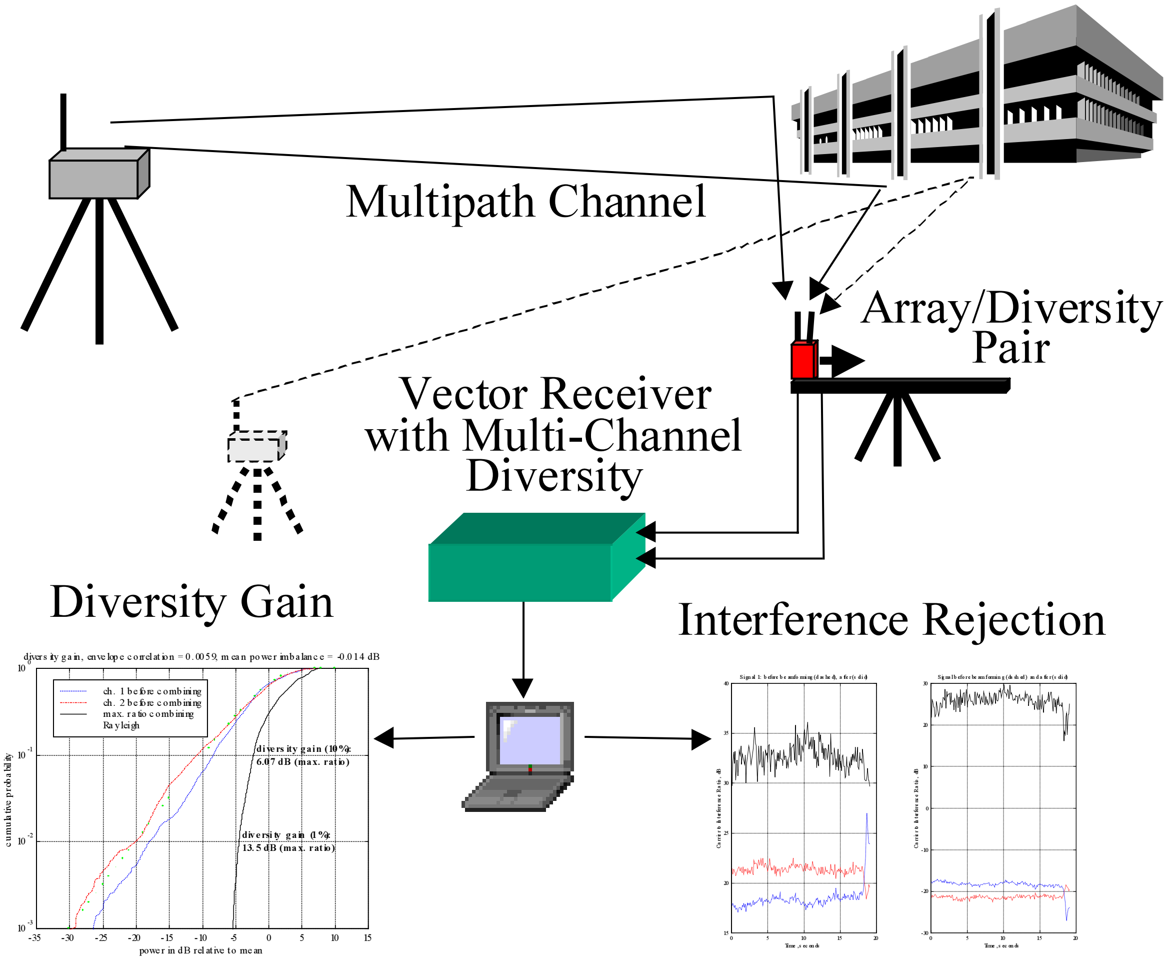


Figure 8-2. Overview of the Handheld Antenna Array Testbed (HAAT)

The handheld receiver unit consists of two receivers packaged in a box having the approximate size and shape of a handheld radio, and a portable DAT recorder (a Sony TCD-D8), used to log data. Two antennas, each connected to a separate receiver, are mounted on the box. The received RF signals are mixed down to an audio IF frequency and recorded on the two channels of a digital audio tape (DAT) recorder. The entire receiver unit is portable so that it can be carried by an operator, and rugged enough that it can be used to perform experiments in a wide variety of locations and conditions.

The HAAT system performance was evaluated using conventional communication link theory. Path loss for a distance r that is greater than 1m is given by

$$PL(r) = \left(\frac{4\pi}{\lambda}\right)^2 r^n \qquad (8.3)$$

where r and λ are in meters, and n is the path loss exponent and is equal to 2 for free space propagation and can be determined empirically for other channels. The transmitters produce a 2.05 GHz CW signal at +27 dBm. The receiver noise floor is approximately –88 dBm with the 100 Hz bandwidth filter that was used for processing data. Calculations using (8.3) yield a range of over 600 m in free space with a minimum mean SNR of 20 dB to allow for Rayleigh fading at the 1% cumulative probability level. In an obstructed channel with a path loss exponent of 3, the maximum range is 74 m. For a minimum SNR of 30 dB, allowing for Rayleigh fading at the 0.1% level, the ranges are 200 m and 34 m, respectively. The non line-of-sight measurements were conducted over distances of less than 50 m, while the transmitter-receiver distance was over 100 m for some of the line-of-sight measurements and the outdoor-to-indoor measurements.

A number of parameters were varied in the controlled experiments, such as the location of the transmitter(s) and receiver, the positioner height and orientation (compass bearing). The height and angles of the transmitter and receiver antennas and antenna supports can also be adjusted. These parameters were recorded for each experiment.

8.3.2 Antenna configurations

Many prior experiments reported in the literature offer mostly anecdotal results because the antennas are not fully characterized. To the extent possible, "pure" cases of spatial, polarization, and pattern diversity were used in these measurements in order to isolate the effects of each variable. This is desirable because if more than one parameter is varied it is difficult to draw conclusions about what characteristics of the antenna configuration contribute to its performance. Antenna configurations were used for space, polarization, and pattern diversity as shown in Fig. 8-3. Spatial diversity measurements used the configuration shown in Fig. 8-3 (a). Two dipole antennas were spaced d apart and d was varied in 0.05 wavelength increments from 0.1 to 0.5 wavelength. Figure 8-3 (b) shows the configuration used for polarization diversity. A dipole and a printed "big wheel" antenna were separated vertically by 0.3λ, which was near the minimum spacing that was physically possible. The big wheel antenna [8.27] has an omnidirectional pattern in the horizontal plane and gain that are similar to a dipole, but is horizontally polarized in the azimuth plane. The gain of the big wheel antenna was measured and was within 1 dB of the dipoles used in the diversity experiments. Measurements in a non line-of-sight channel showed that increasing the vertical spacing between the dipole and the big wheel from 0.3λ to 0.5λ had very little effect on the envelope correlation, indicating that small variations in vertical position were not critical in this configuration. Pattern diversity measurements used two dipoles connected to a 90° hybrid as shown in Fig. 8-3 (c), with *d* fixed at 0.25λ. This yielded two directional patterns with opposing beam maxima directions.

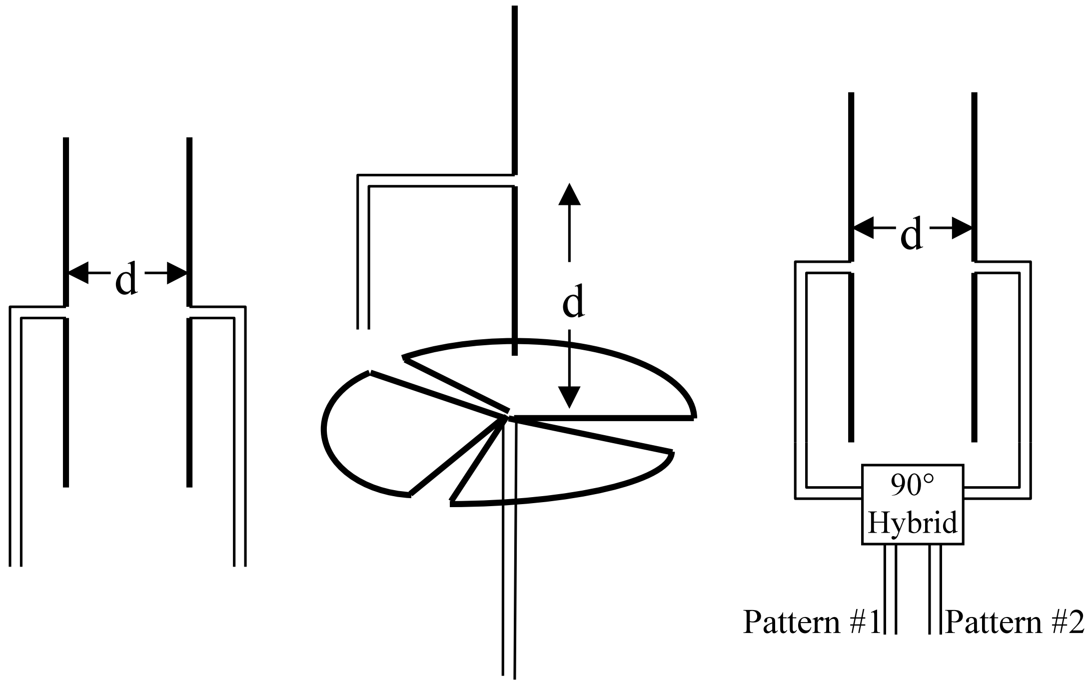


Figure 8-3. Diversity antenna configurations: (a) spatial, (b) polarization, (c) pattern

8.3.3 Mutual coupling

The effects of mutual coupling change the antenna patterns from the free space pattern. In the case of spatial diversity in particular, the change in patterns will tend to decrease the correlation between two closely spaced antennas below the theoretical value [8.12]. This is because the expression in (8.1) was calculated assuming omnidirectional patterns. In a practical system each antenna has a different pattern because of mutual coupling. Therefore, the relative weights of incoming multipath components received by each antenna are different, even when the antennas are closely spaced and the phases of the multipath components received by each antenna are similar. This reduces the probability that the received signals at both antennas will fade simultaneously.

The patterns of each dipole in the spatial diversity configuration of Fig. 8-3(a) were measured on an outdoor range with the first dipole centered over the positioner. The pattern of the each diversity antenna was measured for spacings from 0.1 to 0.5λ. Figure 8-4 (a), (b), and (c) show measured co-polarized azimuth (H-plane) patterns of one of the dipoles for spacings of 0.1, 0.3, and 0.5λ, respectively, with the other dipole terminated. The patterns calculated using the NEC moment method simulation code are included in Fig. 8-4 and agree closely with the measured patterns. The slight asymmetry in the measured patterns is probably due to the antenna feeds, which were not modeled.

If the antennas had pure omnidirectional patterns, the square of the correlation of the complex antenna patterns over azimuth angle would vary as a squared Bessel function of the electrical antenna spacing. This coincides with the function for the envelope correlation from (8.1). Figure 8-4 (d) shows that the squared correlations of the complex patterns are generally lower than the theoretical curve, especially for small spacings. This is because the measured patterns include the effects of pattern distortion due to mutual coupling as well as the effects of antenna spacing on the phase of the received signal.

Mutual coupling also has a significant effect on the pattern diversity. The patterns obtained with the pattern diversity configuration shown in Fig. 8-3 (c) (patterns not shown here) do not coincide with the theoretical cardioid pattern but agree closely with the NEC model of this antenna configuration. The patterns are directional with opposing maxima and a front-to-back ratio of approximately 4 dB.

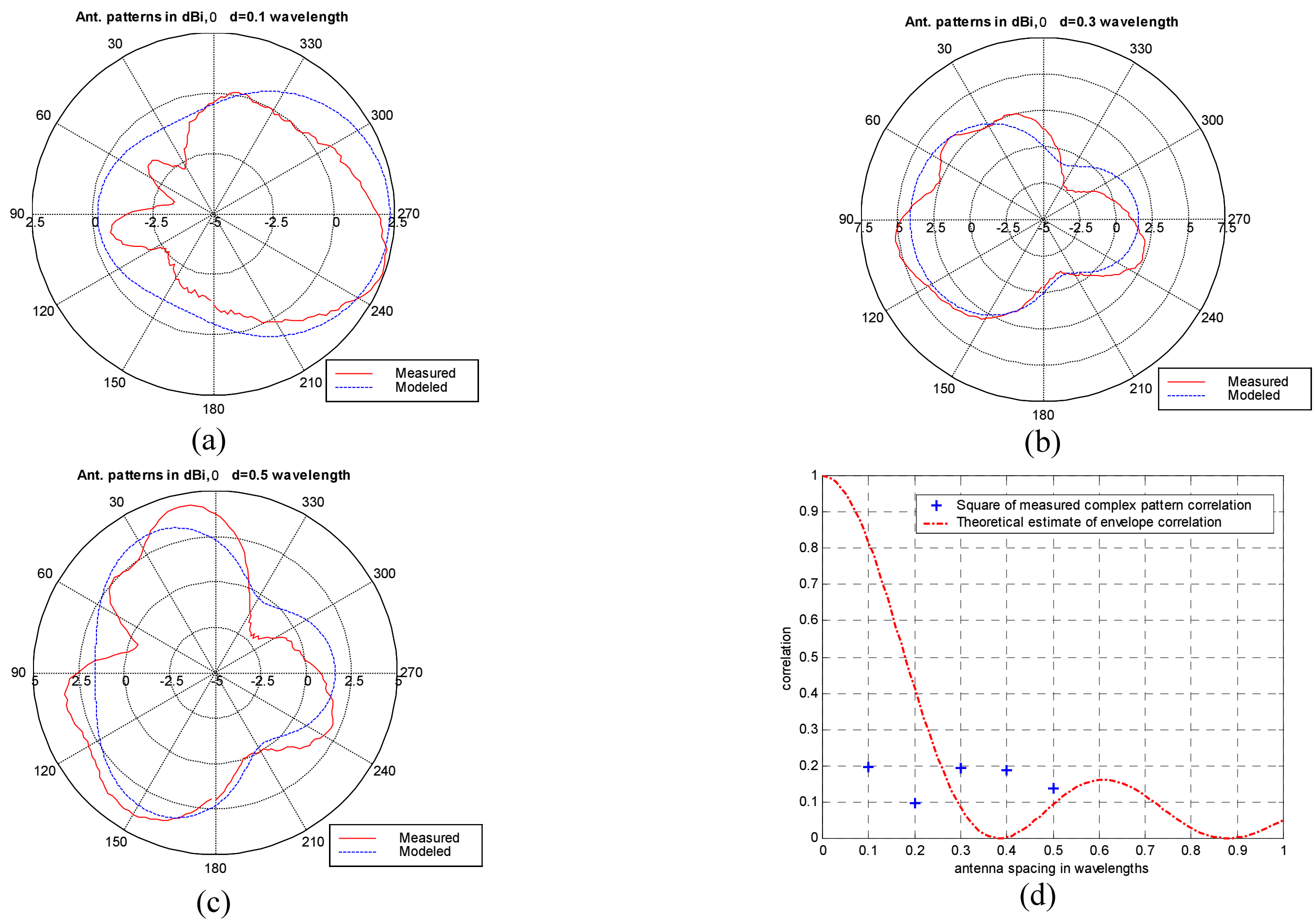


Figure 8-4. Effects of mutual coupling: (a) azimuth pattern of dipole with 0.1λ spacing, (b) azimuth pattern of dipole with 0.3λ spacing, (c) azimuth pattern of dipole with 0.5λ spacing, (d) squared correlation of complex pattern vs. spacing, measured and theoretical for omnidirectional patterns.

8.3.4 Measurement cases

Controlled experiments were conducted using the HAAT in urban, "urban canyon," suburban, and rural locations with flat to mountainous terrain, including both line-of-sight (LOS) and non line-of-sight or NLOS (shadowed) channels. Table 8-1 describes the locations where these experiments were performed. A single transmitter was used in these experiments. The receiver was mounted on the linear positioner and received data was recorded as the receiver moved along the 2.8 m track. Four measurements were taken for each antenna configuration, and the track was rotated 45° in azimuth between measurements to cover a 180° sector to yield representative statistics from all directions. The symmetry of statistics for measurements separated by 180° was confirmed for an urban, non line-of-sight channel. Transmitter and receiver antenna heights were approximately 1.5 m, representing a peer-to-peer scenario.

Table 8-1 Description of diversity experiment locations including line-of-sight (LOS) and non line-of-sight (NLOS) channels

Location	**Description**
Upper Quad area, Virginia Tech campus	Urban, small open area surrounded by buildings (LOS)
Whittemore/Hancock Hall area, Virginia Tech campus	Urban, small area between two buildings (NLOS)
EE Graduate Student Office area, Virginia Tech campus	Suburban, open area with nearby buildings on 2 sides (LOS)
Burruss/ Pamplin Hall area, Virginia Tech campus	"Urban canyon" walkway between rows of buildings (NLOS)
Drill Field, Virginia Tech campus	Suburban, large open area surrounded by buildings (LOS)
Pandapas Pond, Jefferson National Forest	Rural, wooded area on hilltop between two mountains (NLOS)
Boley Fields, Jefferson National Forest	Rural, open area in valley, surrounded by trees and mountains (LOS)
Room 621 Whittemore Hall, Virginia Tech campus	Indoor (NLOS)
Parking lot to room 621 Whittemore	Outdoor to indoor (NLOS)

An additional set of measurements was performed with and without an operator's head in close proximity to the receiving antennas, with the operator walking along side the unit as it moved down the track. These measurements were taken in an urban non line-of-sight location and consisted of eight measurements with the operator and eight measurements without the operator, with the track rotated 45° between measurements. It was necessary to cover the full 360° in azimuth because the operator disrupted the symmetry of the system.

8.3.5 Repeatability of measurements

Repeated measurements over the same track were performed in an indoor controlled environment to test for repeatability. The correlation of the envelopes recorded in successive runs was 0.98. In outdoor measurements with pedestrian traffic, correlations as high as 0.94 were observed between repeated runs. Even when the correlation was lower, the envelope correlation, power imbalance, and diversity gain for repeated measurements were very similar.

8.3.6 Data processing

Data collected with the HAAT was processed off line as described in Chapter 6. Best-fit Ricean CDF, diversity gain at the 10% and 1% cumulative probability (90% and 99% reliability) levels, envelope correlation, and power balance between the receiver branches were calculated. The data were processed with no demeaning and with demeaning using a six-wavelength window.

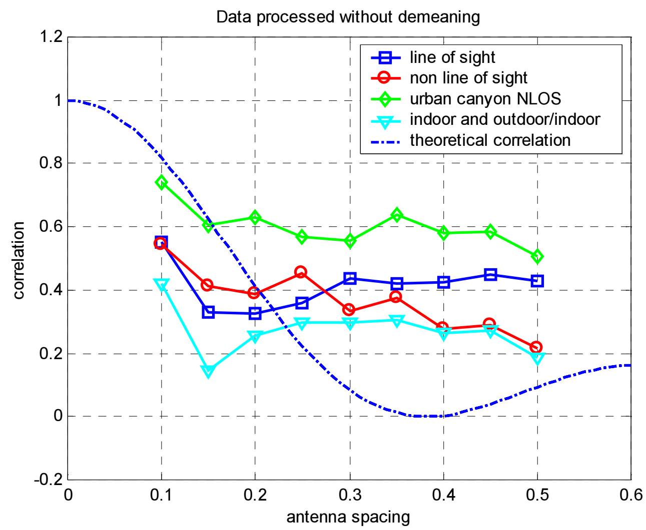
8.4. Experimental Results

Measurements were divided into four categories so that measurement sets within a group represented similar types of channels and had generally similar statistics. As shown in Table 8-2, these categories are line-of-sight (urban and suburban), non line-of-sight (urban and rural), urban canyon (non line-of-sight between rows of buildings), and indoor and outdoor-to-indoor non line-of-sight. These categories were assigned the codes LOS, NLOS, UCN, and IN, respectively. First we discuss the results of the spatial diversity measurements and then polarization and pattern diversity measurements.

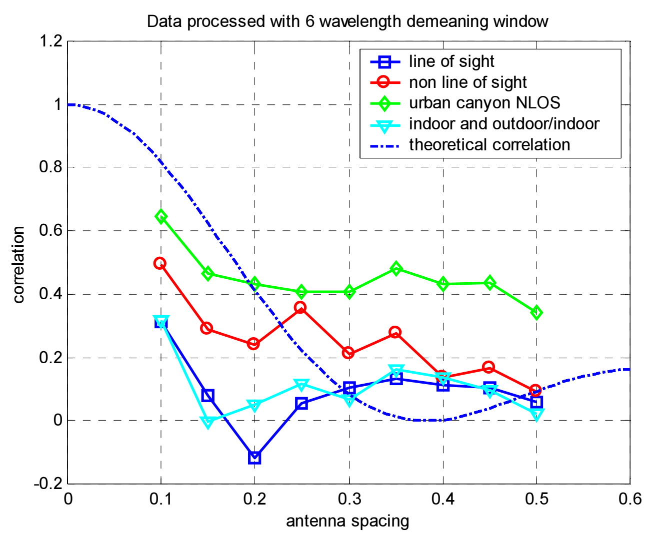
Table 8-2. Categories of measurement sets with statistics of the measurement set mean values. G_{div} is the diversity gain at the 99% reliability level with maximal ratio combining.

	***K* (ratio)**		ρ_e		**G_{div}, dB**	
	μ	σ	μ	σ	μ	σ
Line-of-sight (LOS)	**1.86**	**0.22**	**0.42**	**0.04**	**6.44**	**0.15**
Non line-of-sight (NLOS)	**1.16**	**0.58**	**0.36**	**0.09**	**8.81**	**0.75**
Urban Canyon, non line-of-sight (UCN)	**1.29**	**0.26**	**0.6**	**0.03**	**7.43**	**0.4**
Indoor and Outdoor-to-indoor non line-of-sight (I, OI)	**0.63**	**0.08**	**0.27**	**0.22**	**8.57**	**0.41**

Figure 8-5 shows the envelope correlations from the spatial diversity measurements processed without demeaning and with a six-wavelength demeaning window, as was used in [8.25]. Refer to Section 6.8.1.1 for a discussion of demeaning. The measured correlations are below the theoretical curve for small antenna spacings and above the curve for spacings larger than about 0.2 wavelength. After demeaning the correlations are much lower, although the correlations for the urban canyon measurements still exceed the theoretical curve for spacings of 0.25 wavelength or greater. The correlations for measurements in line-of-sight channels are very low when demeaning is used. However, there is little change in shadowing over the relatively short distances covered by these measurements, so demeaning is not appropriate. The correlation for all spacings is below 0.7, which is typically considered to be the maximum for effective diversity combining. The correlation for the urban canyon channels is highest, probably because the multipath angle spread is relatively small. For line-of-sight measurements the receiver and transmitter were surrounded by buildings and the multipath angle spread should be larger, although the line-of-sight component should dominate. For the indoor and outdoor-to-indoor measurements the fading approaches the Rayleigh distribution, and multipath can be expected to be more evenly distributed than in the other cases. This results in low envelope correlations for spatial diversity configurations in the indoor and outdoor-to-indoor channels.



(a)



(b)

Figure 8-5. Envelope correlations vs. antenna spacing for line-of-sight, non line-of-sight, urban canyon, and outdoor-to-indoor/indoor channels: (a) without demeaning, (b) with 6 wavelength demeaning window

Power balance varied as a function of antenna spacing and ranged from 0.5 to 6 dB. This statistic was not significantly affected by demeaning as shown in Fig. 8-6. The similarity of the statistic for all types of channels, and the relatively large values of power imbalance suggest that the assumption of perfectly uniform angular distribution of multipath that was used to derive (8.2) is not satisfied for any of the channels.

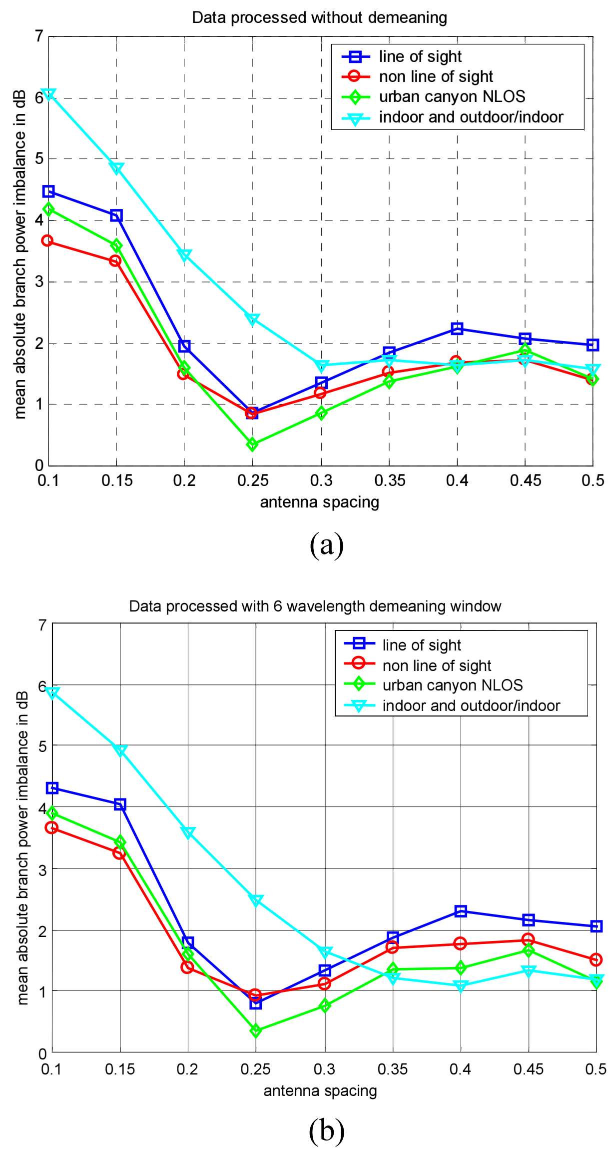
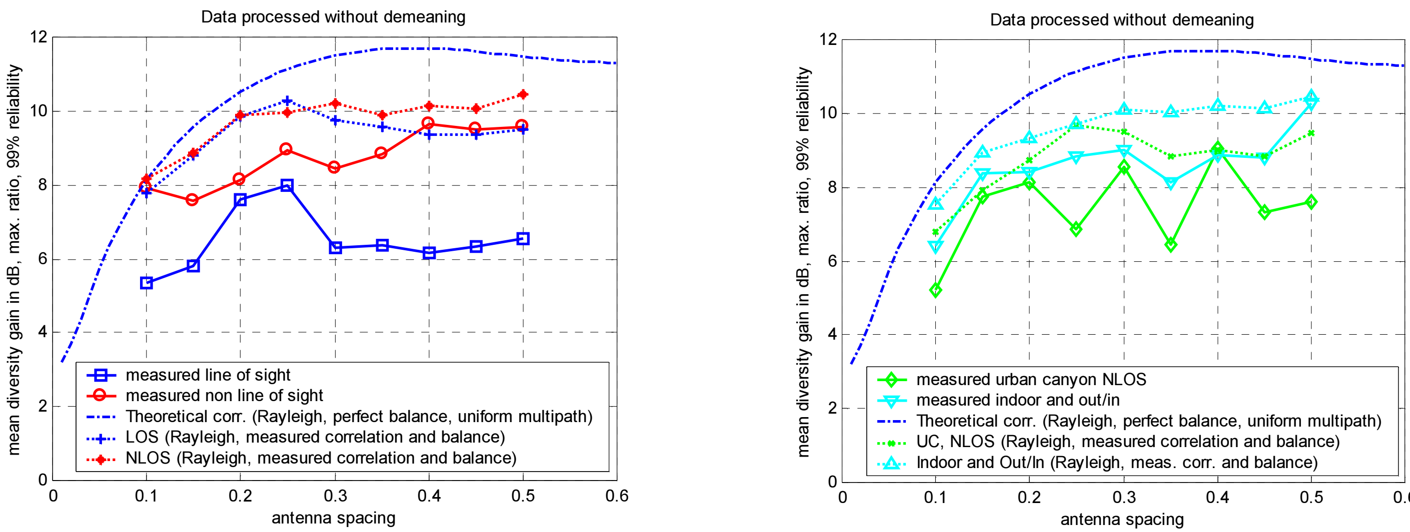


Figure 8-6. Branch power imbalance vs. antenna spacing: (a) without demeaning, (b) demeaned with 6 wavelength window

Figure 8-7 shows the calculated mean diversity gain for maximal ratio combining at the 1% cumulative probability or 99% reliability level. The ideal theoretical curve is obtained from the envelope correlations given by (8.2), for perfect power balance using the approach developed in [8.11]. The other theoretical curves are calculated as in [8.11] but the measured envelope correlations and power imbalances are used. This results in an estimate of diversity gain (without demeaning) that is up to 5 dB lower (for urban canyon and line-of-sight) or up to 4 dB lower (for non line-of-sight and indoor/outdoor-to-indoor) than the estimate using the theoretical correlation and perfect balance. With demeaning, this difference is very similar. The measured results compare more closely to theory when the measured correlations and power imbalance are used in the theoretical calculation. The theory still assumes Rayleigh fading, which was not exactly representative of any of the measured channels (the mean value of the Ricean parameter K for the channels measured ranged from 0.57 to 2.03; K=0 for Rayleigh fading). Demeaning increased the measured diversity gain for some cases and decreased it for others. The mean diversity gain, averaged over all antenna spacings, increased when demeaning was used for urban canyon and indoor/outdoor-to-indoor measurements, but decreased for line-of-sight and non line-of-sight outdoor measurements. These changes were no greater than 0.7 dB, indicating that demeaning has little effect on the diversity gain for these measurements. This may be because the measurements were not done over long enough distances to experience significant changes in shadowing. The measured diversity gain for antenna spacings of 0.2 wavelength or greater is greater than 8 dB for non line-of-sight, non-urban canyon channels.



(a) **(b)**

Figure 8-7. Diversity gain vs. antenna spacing without demeaning for (a) outdoor line-of-sight and non line-of-sight and (b) urban canyon and indoor-to-outdoor/indoor measurements

Results of measurements using spatial, polarization, and pattern diversity configurations are summarized in Table 8-3, categorized by diversity configuration. It can be seen that 7-10 dB diversity gain at the 1% probability (99% reliability) level is typical for spatial diversity with maximal ratio combining in the non line-of-sight channels that were measured. Comparable gains of 6-11 dB can be obtained using polarization and pattern diversity, with small antenna spacings of 0.25-0.3 wavelength. Diversity gains calculated for selection diversity were typically about 1.5 dB lower than those for maximal ratio combining for all antenna configurations.

Pattern diversity and polarization diversity configurations have an added advantage. Even if selection diversity is used, these configurations can provide gain in line-of-sight channels that have very little multipath as well as in fading channels. Polarization mismatches of up to 12 dB or more were observed when transmit and receive antennas were oriented orthogonally. This problem sometimes occurs in operational systems, where handset orientation is random. Polarization mismatch was eliminated when polarization diversity was used.

Table 8-4 shows results of some additional measurements that were part of data set NLOS1A. A spatial diversity configuration using dipoles spaced 0.25 wavelength apart was tested with and without a person's head next to the receiver antennas. The person walked along with the receiver unit as it was moved on the linear positioner. The presence of a human head increased the envelope correlation and power imbalance, and decreased the diversity gain by about 2 dB. Still, a substantial diversity gain of 8.8 dB was calculated at the 99% reliability level.

Table 8-3. Statistics for each measurement location (data processed without demeaning).

Antenna Configuration	Channel	Ricean Parameter *K*	Envelope correlation	Power imbalance, dB	Div. gain in dB with max. ratio, 99% reliability	Div. gain in dB with selection, 99% reliability
Spatial	**NLOS1***	1.00	0.12 – 0.56	0.9 – 2.5	8.9 – 10.3	7.5 – 8.9
	NLOS1A*	0.70	0.12 – 0.49	0.7 – 4.4	7.4 – 10.4	6.0 – 9.0
	NLOS2 *	2.01	0.27 – 0.72	0.6 – 3.8	6.4 – 9.9	4.7 – 8.3
	UCN1*	1.10	0.50 – 0.74	0.4 – 4.5	5.6 – 9.6	4.1 – 8.2
	UCN2*	1.47	0.45 – 0.74	0.3 – 3.8	4.7 – 8.3	3.3 – 7.0
	NLOS3 †	0.92	0.29 – 0.60	1.2 – 3.9	6.2 – 10.6	4.6 –9.0
	LOS1 **	1.95	0.38 – 0.56	1.1 –3.7	4.5 – 7.7	2.9 – 6.0
	LOS2*	2.03	0.23 – 0.48	0.3 – 6.1	4.9 – 8.2	3.1 –6.5
	LOS3 **	1.61	0.30 – 0.69	1.4 – 3.9	4.7 – 7.7	3.2 – 6.1
	OI††	0.68	0.36 – 0.52	1.2 – 5.9	6.1 – 11.3	4.8 – 10.0
	I‡	0.57	-.067 – 0.42	1.6 – 6.2	6.7 – 9.3	5.5 – 7.8
Polarization	**NLOS1A***	0.79	-0.013	3.1	9.2	7.8
	NLOS3†	1.15	-0.052	5.2	8.6	6.8
	UCN1*	1.10	0.26	6.7	6.8	5.3
	UCN2*	1.32	0.12	13.0	3.3	1.9
	LOS1‡‡**	1.48	0.03 – 0.39	4.3 – 4.8	5.5 – 8.7	4.1 – 7.0
	LOS2*	2.06	0.23	3.8	6.3	4.5
	LOS3**	1.45	0.17	8.4	3.9	2.1
	OI††	0.69	0.34	1.5	9.5	8.0
	I‡	0.44	0.07	1.5	10.6	9.5
Pattern	**NLOS1A***	1.20	-0.13 – 0.08	5.6 – 6.2	9.2 – 11.2	7.9 – 9.7
	NLOS3†	0.98	0.12	6.7	6.5	5.3
	UCN1*	1.61	0.31	7.2	6.7	5.2
	UCN2*	1.33	0.32	6.5	7.8	6.1
	LOS2*	2.40	0.22	6.0	3.8	1.7
	LOS3**	1.40	0.19	7.1	4.8	3.7
	OI††	0.58	0.17	5.2	8.9	7.2
	I‡	0.43	0.02	2.3	7.6	6.0

Table 8-4. Statistics for spatial diversity measurement with and without operator's head present, vertical dipoles with d=0.25λ

	envelope correlation	**power imbalance**	**diversity gain with maximum ratio, 99% reliability**	**diversity gain with selection diversity, 99% reliability**
without operator	0.31	0.4 dB	10.6 dB	9.4 dB
with operator	0.44	0.5 dB	8.8 dB	7.1 dB

8.5 Conclusions

Spatial, polarization, and pattern diversity configurations were measured in a variety of channels including line-of-sight, non line-of-sight, urban, suburban, rural, urban canyon, and indoor channels. These channels exhibited fading that was approximately Ricean, with mean values of specular-to-random power ratio K that range from approximately 0.6 to 2.0. This investigation showed that diversity gains of 7-10 dB can be achieved at the 99% reliability level using spatial, polarization, or pattern diversity. Diversity gain of 8-9 dB is typical in non line-of-sight indoor and outdoor channels. These gains can be achieved with antenna spacings as small as 0.1 to 0.15 wavelength. The measurements indicate that polarization diversity configurations can increase SNR by 12 dB or more by eliminating polarization mismatch.

The statistics of the raw data give a realistic estimate of actual system performance. However, the statistics calculated for demeaned data may be useful for comparison with the theoretical envelope correlation. Envelope correlations below 0.7 were observed in all channels by all spatial, polarization, and pattern diversity configurations that had spacings greater than 0.1 wavelength, even without demeaning. Demeaning decreased the envelope correlation but had little effect on the diversity gain for these measurements.

As reported in [8.12], envelope correlation for spatial diversity configurations was lower than predicted by the theory of [8.7]. This effect is caused by distortion of the individual antenna patterns due to mutual coupling. The effects of mutual coupling are not entirely beneficial, since the distorted patterns also cause power imbalance if the multipath is not uniformly distributed in angle. This reduces diversity gain compared to the gain that can be achieved using omnidirectional elements with a similar correlation coefficient. This can be seen in comparisons of diversity gain calculated as in [8.12] using theoretical and measured values for the correlation and power balance.

The measurements reported here were for narrowband signals. When operated in frequency-flat fading environments, wideband radios should experience benefits from diversity combining similar to those seen by narrowband systems. Wideband systems also operate in frequency-selective fading environments that are likely to require different approaches such as adaptive arrays consisting of three or more elements, or diversity combining that includes some form of temporal processing. Wideband experiments are planned to measure channel characteristics and performance of narrowband and wideband combining approaches for diversity reception of wideband signals in channels with varying temporal characteristics.

References

[8.1] W. C. Y. Lee, "Antenna Spacing Requirement for a Mobile Radio Base-Station Diversity," *Bell System Tech. Journal*, vol. 50, pp. 1859-1876, July/Aug. 1971.

[8.2] W. C. Y. Lee and Y. S. Yeh, "Polarization Diversity for Mobile Radio," *IEEE Trans. Comm.*, vol. COM-20, no. 5, pp. 912-923, 1972.

[8.3] A. M. D. Turkmani, A. A. Arowojolu, P. A. Jefford, and C. J. Kellet, "An Experimental Evaluation of the Performance of Two-Branch Space and Polarization Diversity Schemes at 1800 MHz," *IEEE Trans. Veh. Tech.*, vol. 44, no. 2, pp. 318-326, 1995.

[8.4] F. Lotse, J.-E. Berg, U. Forseen, and P. Idahl, "Base Station Polarization Diversity Reception in Macrocellular Systems at 1800 MHz," *46th Veh. Tech. Conf.*, vol. 3, pp. 1643-1646, 1996.

[8.5] D. C. Cox, "Antenna Diversity Performance in Mitigating the Effects of Portable Radio Telephone Orientation and Multipath Propagation," *IEEE Trans. Comm.*, vol. COM 31, no. 5, pp. 620-628, 1983.

[8.6] P. L. Perini and C. L. Holloway, "Angle and Space Diversity Comparisons in Different Mobile Radio Environments," *IEEE Trans. Antennas and Propagation*, vol. 46, no. 6, pp. 764-775, June 1998.

[8.7] R. H. Clarke, "A Statistical Theory of Mobile-Radio Reception," *Bell System Tech. Journal*, pp. 957-1000, July – Aug. 1968.

[8.8] W. C. Jakes, Ed., *Microwave Mobile Communications*, Wiley, New York, NY, 1974. (reprint IEEE Press, New York, 1993.)

[8.9] J. H. Winters, J. Salz, and R. D. Gitlin, "Adaptive Antennas for Digital Mobile Radio," Proc. IEEE Long Island Section Adaptive Antenna Systems Symposium, Long Island, NY, pp. 81-86, Nov. 19, 1992.

[8.10] N. Benvenuto and L. Tomba, "Performance Comparison of Space Diversity and Equalization Techniques for Indoor Radio Systems," *IEEE Trans. Veh. Tech*., Vol 46, no. 2, pp. 358-368, May 1997.

[8.11] K. Dietze, C. B. Dietrich, Jr., and W. L. Stutzman, "Analysis of a Two-Branch Maximal Ratio and Selection Diversity System with Unequal SNRs and Correlated Inputs for a Rayleigh Fading Channel," *manuscript in preparation.*

[8.12] R. G. Vaughan and N. L. Scott, "Closely Spaced Monopoles for Mobile Communications," *Radio Science*, vol. 28, no. 6, pp. 1259-1266, Nov. - Dec. 1993.

[8.13] T. Taga and K. Tsunekawa, "A Built in Diversity Antenna for 800 MHz Band Portable Radio Units," *Proc. IEEE APS Symposium*, pp. 705-708, 1986.

[8.14] K. Tsunekawa, "Diversity Antennas for Portable Telephones," *IEEE Veh. Tech. Conf.*, 1989, pp. 50-56.

[8.15] T. Taga, "Characteristics of Space-Diversity Branch Using Parallel Dipole Antennas in Mobile Radio Communications," *Electronics and Communications in Japan*, Part 1, vol. 76, no. 9, pp. 55-65, 1993.

[8.16] K. Tsunekawa and K. Kagoshima, "Diversity Performance Analysis of Two Parallel Dipole Antennas Mounted on a Small Metal Body," *Electronics and Communications in Japan*, Part 1, vol. 76, no. 10, pp. 80-90, 1993.

[8.17] K. Ogawa, and T. Uwano, "A Diversity Antenna for Very Small 800 MHz Band Portable Telephones," *IEEE Trans. Antennas and Propagation*, September 1994, pp. 1342-1345.

[8.18] S. Mano, M. Kimata, N. Inagaki, and N. Kikuma, " Application of Planar Multibeam Array Antennas to Diversity Reception," *Electronics and Communications in Japan*, part 1, vol. 79, no. 11, 1996, pp. 104-112.

[8.19] G. Dolmans and L. Leyten, "Performance Analysis of an Adaptive Multi-beam Portable Handset in Fading Indoor Channels," *IEEE Antenna & Propagation Society Symposium*, July 1997, pp.342-345.

[8.20] B. M. Green and M. A. Jensen, "Diversity Performance of Personal Communications Handset Antennas Near Operator Tissue," *IEEE Antenna & Propagation Society Symposium*, July 1997, pp.1182-1185.

[8.21] M. LeFevre, M. A. Jensen, and M. D. Rice, "Indoor Measurement of Handset Dual-Antenna Diversity Performance," *IEEE Veh. Tech. Conf.*, 1997.

[8.22] G. Pedersen and S. Skjaerris, "Influence on Antenna Diversity for a Handheld Phone by the Presence of a Person,' *Proc. IEEE VTC* 1997.

[8.23] P. Eratuuli, P. Haapala, P. Aikio, P. Vainikainen, "Measurements of Internal Handset Antennas and Diversity Configurations with a Phantom Head," *IEEE APS Symposium*, pp. 126-129, June 1998.

[8.24] C. Braun, G. Engblom, and C. Beckman, "Antenna Diversity for Mobile Telephones," *Proc. IEEE APS Symposium*, pp. 2220-2223, June 1998.

[8.25] J. S. Colburn, Y. Rahmat-Samii, M. A. Jensen, and G. J. Pottie, "Evaluation of Personal Communications Dual-Antenna Handset Diversity Performance*," IEEE Trans. Veh. Tech.,* vol. 47, no. 3, pp. 737-746, Aug. 1998.

[8.26] M. G. Douglas, M. O. Okoniewski, and M. A. Stuchly, "A Planar Diversity Antenna for Hand Held PCS Devices," *IEEE Transactions on Vehicular Technology*, vol. 47, no. 3, pp. 747-754, Aug. 1998.

[8.27] *The A.R.R.L. Antenna Book, 10th Ed.*, American Radio Relay League, Inc., Newington, CT, pp. 318-320, 1964.