Reverse Link Capacity and Coverage Improvement for CDMA Cellular Systems Using Polarization and Spatial Diversity

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Abstract- **This paper explores the benefits of increased diversity order using spatially separated, polarized antennas at the base station receiver of a CDMA cellular system. Field tests are conducted in real mobile wireless environments. A conventional dual diversity receiver is compared with one that implements four-way diversity combining using spatially separated cross-polarized antennas. Several measured quantities are logged at the base station receiver and the mobile transmitter during a packet data connection at fixed data rate. Existing published results that explore polarization diversity focus on correlation measurements between received signal polarization components. The emphasis of the present study is to quantify reverse link capacity and coverage improvements for a CDMA cellular network as a result of exploiting polarization as an additional source of diversity at the base station receiver.**

I. INTRODUCTION

Mobile wireless channels often exhibit multiple reflections and scattering of the radio signals along with random signal strength variations due to fading. Several diversity techniques have been studied and found practical use in many communication systems in order to improve receiver performance in fading channel environments. Among these, spatial diversity has been commonly used at cellular base station receivers. At a base station site the antenna elements need to be well separated in order for their respective channel fading processes to be uncorrelated. The distance required to achieve this is a function of antenna height, carrier frequency used and angle of arrival spread. It has been determined through measurements that horizontally spaced antennas need to be separated by 10 to 30 times the wavelength in order for the correlation between antenna observations to be less than 0.7 [1]. For North American cellular band (825-850 MHz) this distance corresponds to a range of 4 to 11 meters. Therefore higher order spatial diversity at base station sites has not been popular because of the additional cost associated with strict zoning requirements.

Polarization, as a source of diversity, has been studied as early as 1972 but has not become popular until recently [2]-[6]. Multiple reflections and scattering caused by the radio environment between a mobile transmitter and the base station antennas form a mechanism of decorrelation. In general, the reflection properties that apply to each polarization component is different. This gives rise to different random phase changes for each component. Even if the transmitted polarization is truly vertical, after a random number of reflections it is conceivable that the received polarization along with the random phase of each observation will be uncorrelated.

Considering the variety of radio propagation environments along with mobility it is difficult to establish a theoretical framework to study the diversity provided by polarization. As a result, studies published so far consist of channel sounding using a set of polarized antennas and measurement of correlation between the different components of polarization. Any two orthogonal base polarizations should be sufficient to resolve the received wavefront on a plane of base station antenna apertures. While it seems natural to use vertical and horizontal directions as basis there is a dependence between mean branch signal power and cross correlation between polarization components. In [4] a statistical model is developed that explains this trade-off . According to that model, the average branch power levels are equalized at a cost of increased envelope cross correlation when using $\pm 45^\circ$ polarization components.

Unlike most published results in which cross correlation is measured using a constant power sinusoidal source, this study used a pair of mobile and base station transceivers using a 1.25 MHz bandwidth spread spectrum signal according to the cdma2000 physical layer standard [7]. In Section II the experiment setup is described and in Section III more details are given regarding the test environment and data logging. Sections IV and V contain analysis and discussion of simulation and measured data, respectively.

II.EXPERIMENTAL CONFIGURATION AND METHODS

In order to assess performance improvements provided by spatial and polarization diversity in a real mobile wireless channel a series of field measurements were done. The goal of these measurements is to demonstrate the benefits of using spatially separated $\pm 45^\circ$ polarized (Xpol) antennas as a means to implement four branch antenna diversity at a base station site while keeping the physical dimensions of the antenna tower similar to a conventional vertically polarized (Vpol) dual antenna system.

A block diagram of the experiment setup is shown in Fig. 1. A conventional three sector CDMA base station (BS) hardware was configured to operate as two single sector transceivers with identical coverage area. Each RF front end (RFFE) hardware is designed to provide dual diversity receiver paths and a single transmit path. Since the focus of these measurements was reverse link receiver performance, only one forward link transmit signal was generated and transmitted from one of the dual Vpol antennas. The remaining two RFFEs were each connected to a set of

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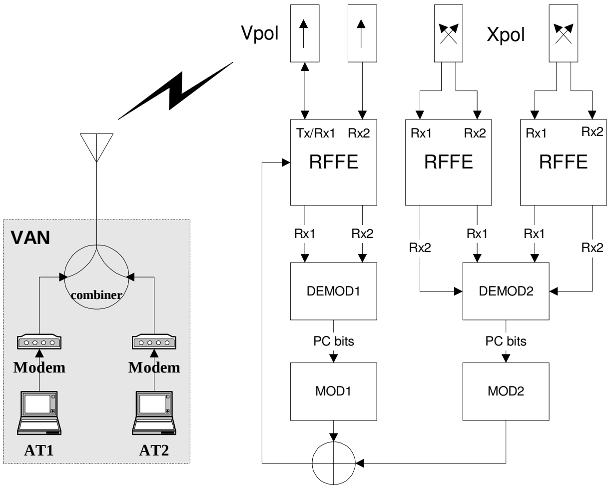

Fig. 1. Field test setup

polarized antenna pair collocated in a single enclosure and spatially separated by the same amount as the Vpol antennas.

The Vpol antennas used in the system were directional panel antennas with dimensions (LxWxD) 116cm x 21cm x 513cm per panel. At the base station site, the antennas were horizontally separated by approximately 15 feet $(\approx 30\times \text{wavelength})$. The Xpol antennas were also directional panel antennas with dimensions (LxWxD) 140cm x 20cm x 7cm per panel. The Xpol panels were also horizontally separated by the same amount and situated such that the same area was covered as the Vpol antenna pair. The Vpol and Xpol antenna specifications were similar so as not to bias the measurements in favor of either pair.

Two access terminals (AT) in a test van were used simultaneously sharing one receive/transmit antenna. In all the field tests both mobiles used the same transmit signal center frequency of 1904.95 MHz. Therefore the mobile radio channel between each AT and the BS receive antennas were identical which allowed a fair comparison of receiver performance.

Two data calls were set up on DEMOD1 and DEMOD2 for AT1 and AT2 respectively. In all test runs a packet data connection at a fixed data rate of 9.6 kbps was established and the link was maintained with a continuous stream of data throughout the test run. Both demodulators implemented maximal ratio combining (MRC) of the branches. The fast inner loop power control was enabled along with a standard outer loop that maintained a frame error rate (FER) of 1%.

The power control bits from each demodulator was punctured onto the respective forward link signals which were transmitted from one of the Vpol antennas as usual. This ensured that there was no significant received forward link signal power difference between the individual ATs. Thus, the open loop power adjustments were the same for both ATs, which allowed us to accurately compare the power transmitted from each AT.

Several different mobile transmit antenna configurations were used in order to explore the effects of polarization diversity:

- vertical antenna magnetically mounted to the roof of the test van
- antenna inside the test van and tilted at various angles relative to vertical

III.SYSTEM PARAMETER SETTINGS

Certain system parameters had to be adjusted to achieve a fair comparison. Specifically, the number of available fingers and finger lock/combine thresholds needed to be adjusted.

The system used in the test allowed only four fingers to be assigned per user. It is reasonable to assume that a specular component of the received signal would in general be incident on all four components of the Xpol antenna pair at the same time. This meant that only one resolvable multipath component could be used by the Xpol antenna RAKE receiver given the number of finger resources available. In order to ensure that the Vpol antenna system was not favored by allowing multiple resolvable paths, the number of fingers was limited to two for the Vpol antenna receiver.

Since the Xpol antennas effectively doubled the combined antenna aperture gain it was expected that the received user signal power per antenna would be halved. That meant the finger thresholds that depend on received signal power needed to be lowered to allow these weaker fingers to be tracked and combined. Therefore the lock and combine thresholds were lowered by 2 dB for the Xpol antenna receiver.

A. *Test area environment*

All data was collected using a Qualcomm test system in San Diego operating at PCS frequencies. Only one isolated sector of a three-sector cell was used with no other neighboring cells active using the same frequencies. The coverage area of the sector that was used in the test is primarily a business area with varying density of buildings and terrain conditions. There is also a small residential neighborhood in the coverage area as well.

The propagation environment and vehicle speed affect the physical layer performance as these factors control the amount of multipath, shadowing and fading processes. Therefore several test runs were conducted in different physical environments and at varying mobile speeds. In addition to stationary and mobility tests at vehicular speeds, pedestrian speed mobility tests were also done with the mobile in an office building. During vehicular speed mobility tests the test van speed varied during the runs and reached up to 60km/hr with occasional stops. Along most of the run route there was no line of sight path between the mobile and the base station. Some runs were conducted traversing the same route in the opposite direction just to add more variation to the measurements. Various mobile transmit antenna orientations were considered in an attempt to emulate typical everyday use of a cellular phone where the transmit antenna is not always vertical.

B. *Data logging*

Several measured quantities were logged both at the mobile station and at the BS during each run. The quantities of interest at the BS receiver for the two ATs were:

- finger status bits (locked, combining, etc.)
- finger path offset
- filtered reverse link pilot channel (R-PICH) SNR for each combining finger
- filtered combined R-PICH SNR

The average total transmit power of each mobile was also logged. Sampling interval for all these measurements was one frame (20 msec).

IV. SIMULATION RESULTS

The expected reduction in per antenna SNR required to achieve 1% FER using four-way diversity combining was characterized through computer simulations. The intent was not to simulate the polarization effects but rather to demonstrate the gain provided by increased antenna aperture and additional diversity in ideal conditions. The mobile channel was modeled with a Rayleigh fading channel characterized by various mobile speeds. For each mobile speed two sets of simulations were run: one using two and another using four-way receive diversity with only one specular path. Further, the fading processes that this specular path experiences on each individual receive antenna were assumed to be uncorrelated. Reverse link fast power control loop was enabled in all simulations. Since there was no outer loop running, several set points were used and the set point required to achieve 1% FER was then computed by interpolation. The carrier frequency used in the simulations was 1885 MHz. The resulting gains for a selection of cdma2000 reverse link radio configurations and data rates are shown in Table 1.

The metric used to quantify the gain is denoted by $\Delta E_c/N_t$ and it is given by:

$$\Delta E_c/N_t = E_c/N_t\big|_{2\text{ way}} - E_c/N_t\big|_{4\text{ way}} \tag{1}$$

where, $E_c/N_t\big|_{n\text{ way}}$ refers to the average SNR per chip for a given antenna in units of dB in order to achieve 1% FER using *n* way diversity combining.

For the RC1 case non-coherent demodulation with equal weight combining is used whereas for the RC3 cases coherent demodulation with MRC is used. Coherent demodulation was implemented by using a pilot phase estimator per antenna observation. Time and frequency tracking loops per antenna were also enabled even though the path offset was constant throughout the simulations and there was no significant Doppler shift due to mobility (radial component of mobile velocity was minimal).

In all cases simulated the general trend seems to be that the overall gain provided by using four-way combining is a function of channel coherence time as parameterized by mobile speed. The largest gains are achieved at moderate mobile speeds (8-30 km/hr). The additional diversity gain that four-way combining provides is outweighed by coherence losses at lower mobile speeds. For moderate mobile speeds the diversity gain increases as a result of increased rate of change of the channel fading processes and overcomes the coherence losses.

As a result of combining four equal strength paths rather than just two a 3 dB reduction of required per antenna SNR should be expected in an AWGN channel and coherent combining. In addition, per antenna SNR should be further reduced in fading channels due to increased diversity provided by four-way combining.

TABLE I

SIMULATION RESULTS

Mobile speed (km/hr)	Per antenna $\Delta E_c/N_t$ (dB)		
	RC1 9.6 kbps	RC3 9.6 kbps	RC3 153.6 kbps
0	2.07	2.50	2.93
3	2.38	2.61	3.09
8	2.94	3.42	3.74
30	3.34	3.38	4.07
100	2.92	3.02	3.57

Simulation results indicate that the expected 3 dB gain for the AWGN channel (0 km/hr) is not achieved in all cases. In the RC1 case this is due the to noncoherent combining loss. Even though phase coherence is possible for the RC3 cases the full 3 dB gain is not achieved for the 9.6 kbps rate. This is due to degraded pilot phase estimation resulting from reduced per antenna pilot E_c/N_t when using four antennas. Notice that for the 153.6 kbps rate this degradation is significantly less. This is because the R-PICH transmit power is increased by 4.5 dB for the 153.6 kbps data rate [7]. It should be mentioned that no attempt was made to optimize the pilot phase estimator for the four-way diversity combining method in order to compensate for the lowered per antenna pilot signal strength. Also, all simulations used the nominal traffic-to-pilot power ratios specified in the cdma2000 standard [7].

In the following a simple model is developed in order to explain the loss due to pilot phase estimation when using four-way coherent combining. Let E_s/N_t and E_p/N_t be the SNR per antenna at the output of the modulation symbol correlator and pilot phase estimation filter, respectively. Assuming the demodulator implements MRC, the soft symbol metric combined over *L* antenna observations can be expressed as:

$$Z = \mathrm{Re}\left\{ \sum_{l=1}^{L} \sum_{j=1}^{N_r} \left(\sqrt{E_s}\, e^{j\theta_{l,j}} b_s + \tilde{n}_{s,l,j} \right) \left(\sqrt{E_p}\, e^{-j\theta_{l,j}} + \tilde{n}_{p,l,j}^{*} \right) \right\} \tag{2}$$

where $\tilde{n}_{s,l,j}$ and $\tilde{n}_{p,l,j}$ are zero-mean complex random variables with and variance N_t. In (2) N_r is the number of modulation symbol repetitions per binary code symbol b_s. Equivalently,

$$Z = LN_r \cdot \sqrt{E_s E_p}\, b_s + \sum_{l=1}^{L} \sum_{j=1}^{N_r} w_{l,j} \tag{3}$$

where $\{w_{l,j}\}$ is a set of uncorrelated zero-mean real random variables with variance $E\{w_{l,j}^2\} = (N_t/2) \cdot (N_t + E_p + E_s)$. The SNR for the combined symbol in (3) can be expressed as:

$$\gamma_T = \frac{2LN_r \alpha \cdot (E_p/N_t)}{(E_p/N_t)^{-1} + \beta}, \tag{4}$$

where we have defined

$$\alpha = \frac{E_s/N_t}{E_p/N_t} = \frac{10^{\rho/10} \cdot G_p \cdot r}{N_p N_r} \quad \text{and} \quad \beta = 1+\alpha \,. \tag{5}$$

Here, ρ is the relative traffic-to-pilot power ratio in dB, G_p is the processing gain measured in chips per modulation symbol, r is the code rate and N_p is the number of chips in the pilot estimation filter (pilot path processing gain).

For a given target combined symbol SNR γ_T, we can solve (4) to get the required pilot symbol SNR per antenna E_p/N_t, or equivalently the combined pilot chip SNR as:

$$\left.\frac{E_c}{N_t}\right|_{L\,\text{way, comb}} = \frac{\beta\gamma_T}{4N_pN_r\alpha} + \frac{1}{N_p}\sqrt{\frac{\gamma_T}{2N_r\alpha}\left(\frac{\beta^2\gamma_T}{8N_r\alpha}+L\right)} \,. \tag{6}$$

Equation (6) can be used to quantify the combining loss due to increased pilot phase estimation errors when using four-way instead of two-way coherent combining. The combining loss is defined as:

$$\Delta E_c/N_t\big|_{\text{comb}} = E_c/N_t\big|_{2\text{way, comb}} - E_c/N_t\big|_{4\text{way, comb}} \,. \tag{7}$$

As an example, consider the data rate 9.6 kbps using RC3. For this case $N_r = 2$, $r = 1/4$, $G_p = 64$, $\rho = 3.75$ dB, $N_p = 3072$ and average γ_T ranges between –2.5 and –1 dB in order to achieve 1% FER for mobile speeds between 0 to 100 km/hr. Using (6) and (7) the combining loss for this data rate is found to be between –0.2 and –0.3 dB. Notice that the derivation above does not include the effects of fast power control. In a power controlled system the received pilot SNR is a random variable which is well approximated with a log-normal distribution. Thus, the combining loss computed as above is less than that observed in simulations. For comparison consider the combining loss for RC3 153.6 kbps data rate. The relevant parameters for this case are $N_r = 1$, $G_p = 8$, $\rho = 10.5$ dB and the useful range of γ_T is between 0.5 dB and 3 dB. Using these parameters the combining loss is computed to be between –0.1 and 0 dB. The combining loss is smaller in this case as a result of increased pilot signal power.

V. ANALYSIS OF EXPERIMENTAL MEASUREMENTS

The experimental data collected was analyzed statistically. The two main metrics of interest in this comparison were:

- the first and second moments of per antenna R-PICH E_c/N_t required to achieve 1% FER
- average mobile transmit power

The first metric can be used to compute reverse link capacity using the two types of diversity receivers. The second metric will be used as a direct indication of increased range as a consequence of reduced mobile transmit power to achieve a given FER. It can also be interpreted as more efficient battery power usage for the same coverage area.

Fig. 2 and Fig. 3 show cumulative distribution functions (CDF) of the per antenna received pilot SNR and mobile transmit power respectively, computed from a sample field test run.

As expected, the received signal SNR is well approximated by a log-normal random variable. The CDFs of such log-normal random variables with suitable parameters are also shown as dashed lines in Fig 2. Mean and standard deviation for Vpol are –21.5 dB, 1.8 dB and for Xpol they are –24 dB and 2.4 dB. The metric $\Delta E_c/N_t$ is computed as defined in (1). The difference between average transmit power of AT1 and AT2 will be denoted ΔP_{Tx} and it is given by:

$$\Delta P_{Tx} = P_{Tx}\big|_{Vpol} - P_{Tx}\big|_{Xpol} \tag{8}$$

where, $P_{Tx}\big|_{Vpol}$ is the average transmit power from AT1 which is received on the Vpol antennas.

A summary of all field measurements is shown in Table 2. As mentioned before a number of runs were conducted at different mobile speeds using various transmit antenna orientations. During some vehicular speed measurements the mobile transmit antenna was magnetically mounted on the roof of the test van (labeled outside vertical). In other vehicular speed test runs the common transmit antenna was inside the test van and could be oriented as vertical, horizontal or tilted. During the pedestrian speed tests the mobile was inside an office building. Stationary tests were carried out while the test van was parked in a lot. Several mobile antenna orientations were tried as for the vehicular runs.

The results of the test runs for vehicular speeds can be summarized as:

- the average measured $\Delta E_c/N_t$ gain is 2.2 dB[1]
- the average measured ΔP_{Tx} gain is 6 dB

The $\Delta E_c/N_t$ gain is lower than predicted by simulations. Some reasons for this observation may be as follows. Simulations assumed static channel conditions characterized by a fixed mobile speed whereas the speed was variable during measurements. Similarly, the number of combining fingers and their respective path delays were kept constant in the simulations which was not the case in a real radio propagation environment. Moreover, the simulation model applied uncorrelated fading processes per antenna observation. In reality, channel fading experienced by the receive antennas were likely to be correlated. This is especially the case for a collocated pair of polarized Xpol antennas.

The last column of Table 2 lists the measured difference in dB between combined SNR per chip using 2-way and 4-way diversity which is defined as in (7). Notice that the combined SNR for the Xpol system is less than that of the Vpol system for all the test runs. This is due to increased combining losses as a result of degraded phase reference estimates and also possible correlation between $\pm 45^\circ$ slants of the collocated

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[1] The two lowest measured $\Delta E_c/N_t$ values were excluded in averaging as they seem to be outliers.

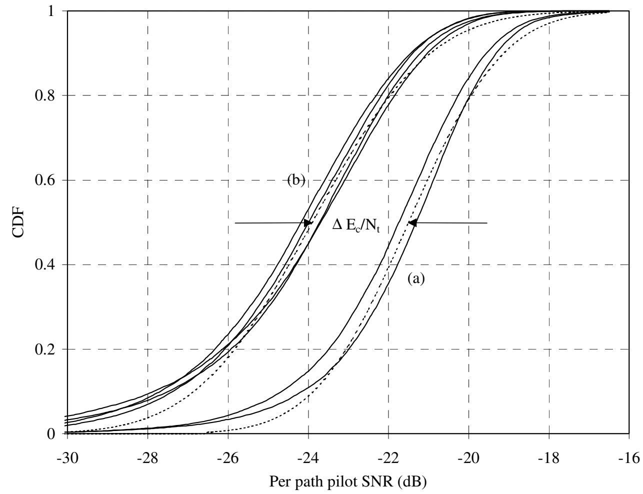

Fig. 2. CDF of received pilot SNR for a sample field test run. (a) two way diversity Vpol antennas (b) four way diversity Xpol antennas

Xpol antennas. In fact, in almost all the cases the loss in combined SNR is approximately equal to the difference between the measured $\Delta E_c/N_t$ and expected average gain of 3 dB.

The $\Delta E_c/N_t$ gain for pedestrian tests is only about 1.6 dB. As mentioned earlier the mobile unit was inside an office building during the pedestrian test runs. Only two test runs were possible both in the same building. Therefore we believe that there is not enough data points to draw any reliable conclusions.

The variability in the $\Delta E_c/N_t$ gain is larger between runs for the stationary tests. Upon inspection of logged measurements this was found to be dependent on mobile location and the amount of shadowing on each receive antenna. On certain runs only one Vpol antenna or one polarization component of a Xpol antenna contributed significantly.

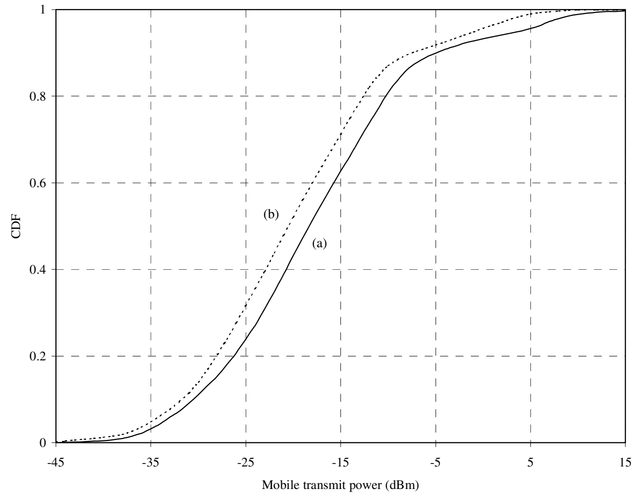

Fig. 3. CDF of mobile transmit power for a sample field test run. (a) two way diversity Vpol antennas (b) four way diversity Xpol antennas

TABLE II

FIELD MEASUREMENTS USING 2 VPOL AND 2 PAIRS OF XPOL ANTENNAS

Mobility	AT Configuration	ΔP_{Tx} (dB)	ΔEc/Nt (dB)	Δ Ec/Nt |$_{comb}$ (dB)
Vehicular	outside vertical	4.85	2.27	-0.70
		4.93	2.24	-0.82
		5.43	2.29	-0.73
		6.04	2.09	-0.91
		4.07	2.16	-0.78
	inside vertical	6.72	2.21	-0.76
		5.14	2.26	-0.69
		5.48	2.21	-0.80
		6.01	1.66	-1.29
	inside 45deg tilt	8.46	2.25	-0.65
		6.15	2.10	-0.86
		6.38	2.14	-0.86
		5.73	2.18	-0.82
	inside horizontal	7.51	2.02	-0.93
		3.68	2.14	-0.77
		5.58	1.71	-1.28
		6.81	2.31	-0.64
Ped	45deg tilt	5.28	1.92	-0.96
	horizontal	5.67	1.63	-1.34
Stationary	outside vertical	3.71	2.20	-1.00
		1.26	2.45	-0.56
	inside vertical	2.18	2.14	-1.05
		0.61	2.10	-0.46
	inside 45deg tilt	6.01	1.24	-1.79
		0.23	2.10	-0.40
	inside horizontal	1.14	2.08	-0.49
		2.42	2.23	-0.69

Another observation from the measurements is that the results did not depend noticeably on mobile antenna orientation. The computed gains are consistent over all the different test runs and mobile antenna orientations.

The measured reduction in required per antenna SNR can be translated to reverse link capacity measured in Erlangs. In [8] it is reported that an average reduction of 2.2 dB per antenna SNR is equivalent to increasing reverse link capacity by 1.7 times.

Turning our attention to the mobile transmit power it is interesting to note that ΔP_{Tx} is larger than the measured reduction in $\Delta E_c/N_t$. There are two factors contributing to this observed phenomenon: first has to do with better power control as a result of the additional diversity provided by using four way combining and second the additional gain provided by the polarized receive antenna components.

In the following a theoretical framework will be developed that explains how diversity gain improves performance of an ideal reverse link power control loop. The probability distribution function of the output SNR of an *M*-branch MRC combiner can be expressed as:

$$p(\gamma) = \frac{\gamma^{M-1} \cdot e^{-\gamma/\bar{\gamma}_M}}{\bar{\gamma}_M{}^M (M-1)!} \tag{9}$$

where, $\bar{\gamma}_M$ is the average SNR per branch. Equation (9) assumes that each antenna observation experiences

TABLE III

FIELD MEASUREMENTS USING 2 VPOL AND 1 PAIR XPOL ANTENNAS

Mobility	AT Configuration	ΔP_{Tx} (dB)	ΔEc/Nt (dB)	Δ Ec/Nt $\vert_{\text{comb}}$ (dB)
Vehicular	outside vertical	0.92	-0.31	-0.39
	inside vertical	0.67	-0.38	-0.42
	inside 45deg tilt	2.40	-0.10	-0.20
	inside horizontal	3.04	-0.16	-0.25

independent Rayleigh fading. The fast inner power control loop commands are generated from an estimate of the combined SNR γ. The ideal action of fast power control would be to maintain a constant SNR γ_d by applying a power gain proportional to the inverse of the measured combined SNR (i.e., $G_{PC} = \gamma_d/\gamma$). The average mobile transmit power will then depend on the statistics of $1/\gamma$. Specifically, the average power gain applied using two-way or four-way diversity can be expressed as:

$$\mathrm{E}\{G_{PC}\} = \begin{cases} \gamma_d/\bar{\gamma}_2 & \text{for } M = 2 \\ \gamma_d/(3 \cdot \bar{\gamma}_4) & \text{for } M = 4 \end{cases} \tag{10}$$

The ratio of power gain using two-way diversity to that using four-way diversity is given by $3 \cdot \bar{\gamma}_4/\bar{\gamma}_2$. Therefore, assuming $\bar{\gamma}_2 = 2 \cdot \bar{\gamma}_4$ there is an additional reduction in average power by $3/2 \cong 1.76\,\text{dB}$. This additional average power reduction is a direct consequence of the increased order of diversity. Of course, the above discussion applies provided that the power control loop is effective in inverting the channel fading process. Using a practical power control loop implementation this condition is usually met approximately for slow changing channel environments (i.e., mobile speeds less than 10 km/hr). In fact, using a channel emulator programmed to generate independent Rayleigh fading processes with a Doppler spectrum corresponding to a mobile speed of 3 km/hr a lab test was done validating the above explanation. In this test the mobile transmit power was measured to be 4.3 dB less when four-way diversity was used compared to two-way diversity. Note that the measured power reduction in this case is approximately 0.5 dB less than the expected 4.8 dB. This difference is due to combining losses resulting from imperfect phase reference estimation which is not considered in (9).

In order to compare the amount of diversity provided by polarization and that of horizontal separation, another receiver configuration was tested in the field. In this test the receiver for AT1 was unaltered but the receiver for AT2 was configured such that it had access to only one collocated pair of $\pm 45^\circ$ polarized antenna elements. Four test runs using different mobile antenna orientations were carried out. The results of these test runs are shown in Table 3.

It is seen that there is a small loss which is reflected by the measured $\Delta E_c/N_t$ and $\Delta E_c/N_t\big|_{\text{comb}}$. A reason for this loss may be higher correlation between fading processes experienced by the collocated elements of the Xpol antenna. An interesting observation is the significant difference in the transmitted mobile power when the mobile antenna was tilted. This supports the conjecture that the cross polarized antenna elements may be more effective in resolving received waveform components that are not vertically polarized. Similar observations have been reported earlier in [9].

VI. CONCLUSIONS

Polarization provides a compact and effective form of diversity that may be exploited by using collocated cross polarized antenna elements. Polarization diversity alone is almost as effective as spatial diversity when using two-way combining. However, their compact size makes it feasible to implement four-way diversity by using two spatially separated pairs of cross polarized antenna elements. Field measurements carried out in a real mobile wireless channel environment resulted in a reduction of required per antenna SNR by about 2.2 dB when the receiver implemented four-way combining using a combination of spatial and polarization diversity. This translates to a reverse link capacity increase by about 1.7 times that achieved using dual spatial diversity alone. In addition to capacity increase the average mobile transmit power is reduced by 6 dB for the same quality of service. This can be interpreted as increased cell coverage area or battery power savings for the same coverage area. Reduced received signal power per antenna poses new challenges for efficient future receiver designs

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