On Polarization Transmit Diversity in CDMA Régimes

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Abstract

This paper considers *transmit diversity* schemes applied to cross-polarized linear antennas at cellular base-stations, with a single linearly polarized antenna used by the mobile station receiver. The performance of Space-Time Block Code (STBC) and Time-Delay Transmit Diversity (TDTD) is analyzed as a function of the relative orientation of the transmit and receive antennas. It is shown that power gain and diversity gain interplay as a function of the relative polarization orientation angle and affect the bit error-rate (BER) performance. The method of *polarization matching* is reviewed [8], and its power-BER performance advantage explained. Finally, a new method that combines polarization transmit diversity with polarization matching is presented. This new enhanced transmit diversity is suitable for 3G cellular systems without any further modifications required in the mobile station. The system performance for this new method is presented, and compared with the former polarization transmit diversity schemes.

1 Introduction

Mobile wireless channels are governed by time varying statistical characteristics as the mobile station moves around [1]. Well-known phenomena including shadowing, fading, Doppler shift, and polarization mismatch greatly affect the communications link performance. Multipath-generated fading has a detrimental effect on the average bit error-rate (BER) performance of a receiver-detector. In the case of non-fading additive white Gaussian noise (AWGN) channel, the detected BER decreases in exponential-order as a function of the received signal-to-noise ratio (SNR), or alternatively, with the bit energy to noise spectral density (E_b/N_0). However, in a Rayleigh fading channel the BER turns into a polynomial-order decreasing function of E_b/N_0 [1]. There are several strategies aimed at alleviating the fading penalty in digital cellular systems: One is *power control*; this method has a limited advantage for CDMA systems in the down-link (from the base-station – BS, to the mobile station – MS). The reason being the incurred in-cell signal-induced interference generated via non-orthogonal multipath. This channel dependent effect restricts the practical power control range to less than 10dB in IS-95, and 20dB in UMTS. The second approach is to apply *diversity transmission*; this constitutes a family of methods, all of which aim at allowing the receiving end to exercise multiple replicas of the transmitted information that suffer *independent* fading. By exploiting the independence in fades it is possible to recover a significant amount of the lost BER per given E_b/N_0.

Among the diversity methods utilized in CDMA systems we refer in this paper to delay, space, and polarization diversity schemes. Delay diversity relies on the property of minimum correlation between replicas of a direct-sequence (DS) spread-spectrum signal, delayed with respect to each other by more than the chip duration. A rake matched filter receiver recovers via maximal-ratio receive combining (MRRC) the delayed replicas of the signal to enhance the effective SNR into the detector[1]. Using two co-polarized spaced antennas (spacing of BS antennas is a function of the angle spread of the scattered signal, and 10λ - 20λ represents the typical spacing range, where λ denotes the signal wavelength) for reception and/or transmission guarantees relatively low correlation between the fading of the signal in each antenna. It is well known that diversity provides a significant improvement (depending on the BER operating point), and that equal power diversity is superior to unequal power case.

The E_b/N_0 improvement for a given BER at the detector output is termed diversity gain, with respect to the performance without diversity for the diversity branch with highest mean power. Generally, the 2-branch diversity gain G (in dB) depends on the correlation between fades (ρ) and the mean power difference Δ (in dB) between the two received signals.

[1] In two-branch MRRC the output SNR equals the sum of input SNR's.

An empirical expression for MRRC diversity gain at 90% signal reliability is [2]:

$$G = 7.14 \cdot \exp\left(-0.59\rho - 0.11\Delta\right) \qquad (1)$$

Thus, In general, the diversity gain is the highest for equal power inputs, which are uncorrelated. Unequal power at the diversity branches, and/or correlation between the inputs reduces the diversity gain with respect to the highest power branch [2].

The *space diversity* technique has been traditionally used in cellular BS's for the enhanced up-link (from the MS to the BS) reception, with a dual-channel receiver incorporated in each BS sector's radio equipment. Due to space limitations and zoning problems, operators have been driven to restrict the span of their sector antennas spacing, and are looking increasingly at installations with dual-polarized sector antennas which are compact and offer low-correlation between the faded signal replicas at the two orthogonal polarizations. Using the same sector diversity receivers with dual-polarized antennas leads to *polarization diversity*.

The diversity gain with polarization diversity depends on the relative orientations of the MS antenna with respect to the BS antennas. In this case (in contrast to space diversity) the power levels at the diversity branches are generally unequal, with a penalty in diversity gain.

The CDMA down and up link channels are essentially different. The down-link quality (E_b/N_0) varies between 2.5dB to over 10dB, depending on channel conditions, which reduces the system capacity and hampers its optimization.

Transmit diversity is more difficult and less efficient than Rx diversity, both due to the need for doubling the Tx power and the deficient combining methods.

Nevertheless, an important problem solved by transmit-diversity is the deep fading experienced with slow-mover mobiles in single-ray Rayleigh channels.

In the rest of this paper we focus on polarization transmit diversity, with emphasis on CDMA régimes.

2 Transmit Diversity

The objective of transmit diversity (TD) is to achieve redundant replicas of the transmitted information through independently fading channels at the receive station in a way analog to that used in receive diversity. To that end the same information is transmitted by two or more antennas thus providing independently fading channels between transmit and receive antennas. To achieve the low correlation between fading in these channels, the antennas must be spaced sufficiently far from each other if all are at the same polarization (space diversity), or may be used in orthogonal polarizations (polarization diversity). The encoding of the information into the transmit antennas, combined with a suitable decoding algorithm at the receive station is referred to as *space-time (S-T) coding* and has been a subject of intensive research in the last few years. Reference [4] presents a short account on the recent evolution of TD algorithms.

One class of algorithms applies a dual antenna TD with one regular transmission via the main antenna, and a delayed re-transmission of the information through a diversity antenna. The (narrow-band) receiver uses an equalizer to demodulate the information. This approach constitutes a 'repetition code', and was applied also in CDMA systems where a delayed version of the main antenna transmitted signal is transmitted via the diversity antenna (the delay should be more than the spreading chip duration). At the Rake receiver the two transmitted signals appear as two sets of 'fingers' and are summed with a MRRC. This method is termed *time-delay transmit-diversity* (TDTD) and provides TD employing a very simple realization, with no modifications required at the MS.

Another method that is used in this work belongs to the simple class of S-T block codes (STBC) by Alamouti [3]. A member of the family of STBC was applied in the recent WCDMA 3GPP standard for TD at the BS [5].

It is common to compare system performance under fixed total transmitted power. Thus, with a dual-antenna TD each antenna transmits 50% of the power transmitted from a reference single antenna.

It was shown in [3] that an equal power 2-Tx antennas STBC performs 3dB worse than an equal power 2-Rx antennas MRRC.

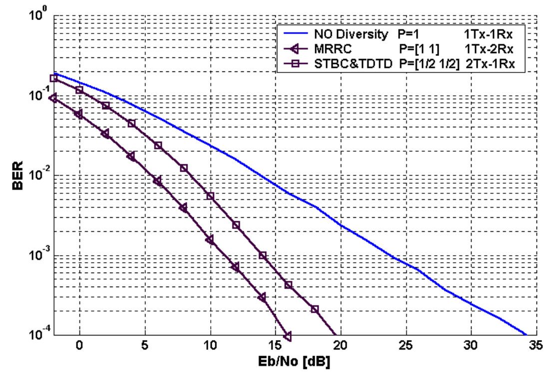

Fig. 1: **STBC and TDTD BER Performance**

Figure 1 presents results obtained by Monte Carlo simulations for an uncoded binary phase-shift keying (BPSK) signal over a Rayleigh fading channel with AWGN. The performance of STBC is shown with relation to the MRRC and the case with no diversity.

In its simplest form, STBC transmits an encoded block of two symbols denoted s_0 and s_1, via two distinct antennas and independent channel responses to the single receive antenna. The channel response is described as multiplicative complex constants h_0 and h_1, between each transmit antenna and the receive antenna. It is assumed that the channel response does not change over two symbol durations.

The received encoded signal $r(t)$ at two consecutive symbol epochs (denoted by r_0, r_1) is given by [3]:

$$r_0 = h_0\, s_0 + h_1\, s_1 + n_0$$

$$r_1 = -h_0\, s_1^* + h_1\, s_0^* + n_1 \qquad (2)$$

The noises n_0 and n_1 are statistically independent stationary AWGN ~ $(0, \sigma^2)$. At the receiver a linear combiner operates on r_0, r_1 using the known h_0 and h_1, performing a decorrelation operation:

$$\begin{pmatrix} \tilde{s}_0 \\ \tilde{s}_1 \end{pmatrix} = \begin{pmatrix} h_0^* & h_1 \\ h_1^* & -h_0 \end{pmatrix} \begin{pmatrix} r_0 \\ r_1^* \end{pmatrix} =$$

$$= \left(|h_0|^2 + |h_1|^2\right) \begin{pmatrix} s_0 \\ s_1 \end{pmatrix} + \begin{pmatrix} h_0^* & h_1 \\ h_1^* & -h_0 \end{pmatrix} \begin{pmatrix} n_0 \\ n_1^* \end{pmatrix} \qquad (3)$$

Thus, with each antenna transmitting half the power P, each symbol enters the detector with (relative) power $\frac{1}{2}P\,(|h_0|^2 + |h_1|^2)^2$ and AWGN power $\sigma^2\,(|h_0|^2 + |h_1|^2)$. Also, it is easily shown that the noises at the output of the combiner are uncorrelated. In [3] it is shown that the resulting combined signals are equivalent to that obtained from two-branch MRRC. Indeed, the SNR out of the detector is the sum of the received SNR's, per symbol:

$$SNR_{out} = \tfrac{1}{2}\, P\, (|h_0|^2 + |h_1|^2) / \sigma^2 = SNR_0 + SNR_1 \qquad (4)$$

In TDTD the MS receives at the two branches independently fading replicas of the same DS-CDMA symbol with additive uncorrelated noises. Using the same notation as for STBC and recalling that each BS antenna transmits half the power P, the MS receives in each symbol epoch the following de-spread signal:

$$r = h_0\, s(t) + \acute{n}_0 + h_1\, s(t-\tau) + \acute{n}_1 \qquad (5)$$

where $s(t)$ is the symbol from one Tx antenna, $s(t-\tau)$ is the delayed symbol from the other Tx antenna, both as distinct 'fingers' after de-spreading. The signals n_0 and n_1 denote the equal-power (σ^2) uncorrelated additive noises (including thermal noise, and other-cell interference) around each 'finger', thus these two waveforms have disjoint time supports. Note that the transmissions to other in-cell users, which are orthogonal in the flat fading case, will appear as additional noise with TDTD! Assuming a significant processing-gain and ignoring the in-cell interference we get for the SNR per 'finger':

$$SNR_0 = \tfrac{1}{2}P\, |h_0|^2 / \sigma^2,\ SNR_1 = \tfrac{1}{2}P\, |h_1|^2 / \sigma^2 \qquad (6)$$

After the MRRC at the Rake receiver the SNR_{out} will be similar to that in (4). Thus TDTD in CDMA operates similarly to the STBC on the signal and thermal noise, at the cost of induced in-cell noise (assuming that the CDMA Rake receiver is capable of handling all the significant 'fingers').

When applying TD to cross-polarized BS antennas, the MS receiver will receive generally two signals of unequal power. This will affect the performance at the output of the MRRC. An STBC polarization TD scheme with cross-polarized dual-transmit and dual-receive antennas, which are matched in orientation, was considered in [7].

Simulation results for several cases of polarization TD are presented in Figure 2. The transmit antennas are assumed to be at ±45º and the receive antenna in a parallel plane and at several orientations. When the MS antenna is vertical, the received power from each transmission will be ¼ (this is the [¼, ¼] case). When the antenna is at 45º only one transmission will be received, assuming very large cross-polarization discrimination[2] (XPD). This corresponds to the [0, ½] case. Finally, when the MS antenna is at 15º off the vertical position (thus at 30º and 60º off the transmit antennas) the received powers will be [1/8, 3/8].

The same behavior will repeat itself with the MS orientation changing over the 4 possible quadrants.

A very important phenomenon noticed here is the interplay between power and diversity gain.

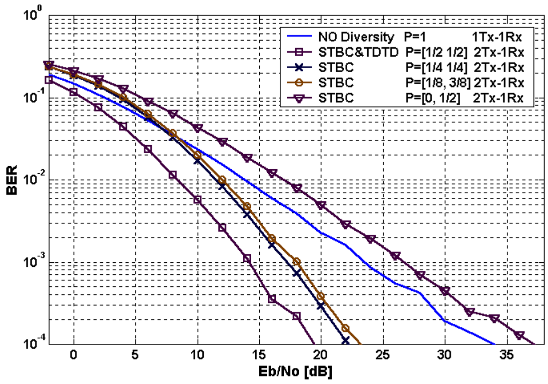

Fig. 2: **STBC and TDTD Polarization Diversity**

Thus, the performance with the diversity is much superior to that with a single stronger signal, but

[2] In Section 3 we expand on the finite XPD cases.

without diversity, even when the branches are different by 4.8dB

The consequence is that when STBC and TDTD are applied as polarization TD, the performance will vary significantly with the orientation of the MS antenna with respect to the BS antennas.

3 Polarization Matching

The electromagnetic radiation is polarized, and allows for two orthogonal polarization states. No antenna can be matched simultaneously to both polarizations. The propagation of the signals through an inhomogeneous medium and through scattering may transfer part of it to the orthogonal polarization. This is the case for terrestrial communications, for example, and in particular in urban areas, where the signals encounter multipath from objects on the way. The transfer of polarization has been found to be typically -10 dB in rural areas, -7.8 dB in urban areas and as high as –4 dB indoors [6]. The orthogonal polarization components have been found to have an independent fading pattern, with correlation lower than 0.6, and similar fading statistics.

Cellular systems operate traditionally in vertical polarization, with an a-priori mismatch of the polarization between the hand-held terminal and the BS antenna.

The channel XPD values are large enough to cause significant polarization mismatch losses. Another important result is that the short-term average polarizations of signals at two distinct frequencies (e.g. those of down and up links) with same antennas and through the same channel are highly correlated [8]. This may be termed polarization shadowing. This leads to the *polarization matching* technique[3] that continuously varies the polarization of the signal transmitted from the BS so as to match the short-term average polarization of the MS [8], [9]. The information on the polarization of each MS is derived at the BS from the measured received signal polarization.

This technique is not dependent on feedback from the MS, is robust at higher MS speeds and does not require any cooperation from the MS.

When applied in a system with cross-polarized BS antennas, it may improve the performance of the power deprived users by up-to the XPD, and greatly enhance the signal quality, as well as improve power efficiency and reduce the generated interference by a few dB's.

[3] Patent Pending.

4 Transmit Diversity with Polarization Matching

It was shown that the performance of a polarization TD scheme depends on the relative orientation of the BS and MS antennas. When the mean power received by the mobile antenna from the two transmit antennas is the same, the performance is best. This requires that the magnitude of both angles between the mobile antenna and BS antennas be 45º. Thus, by applying TD (such as STBC or TDTD) combined with polarization matching it is possible to achieve the best possible performance of polarization TD regardless of the MS antenna orientation[4].

Based on equation (1), and assuming $\rho=0$, the diversity gain in dB for polarization TD is given by:

$$Gain\,[dB] = 7.14 \cdot \exp\left\{ -0.11 \cdot \left| 10\log_{10}\left[\frac{\cos^2(45-\varphi)}{\cos^2(45+\varphi)} \right] \right| \right\} + 10\log_{10}\left\{ \max\left[\cos^2(45-\varphi), \cos^2(45+\varphi) \right] \right\} - 3 \quad (7)$$

Figure 3 summarizes graphically the relative link performance for polarization TD, polarization matching combined with TD, and polarization matching (with no TD) as a function of the MS angle orientation in the plane defined by the BS antennas.

The BS antennas are indicated at the center of the plot and are at ± 45º. The TD case follows Equation (7), and its performance varies over a 4dB range.

Finally, it is important to note that with no TD applied, but with polarization matching (which still uses the two cross-polarized antennas at the BS) the relative received power at the MS is *P*, or 0dB in the same scale considered before.

[4] In addition to polarization mismatch there is a gain loss due to orientation of the mobile antenna and its radiation pattern. This gain 'mismatch' is not recoverable by polarization matching, and is not consider here any further.

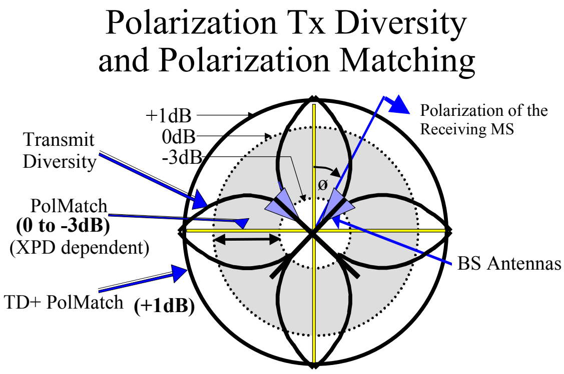

Fig. 3: **STBC/TDTD with Polarization Matching**

The amount of recoverable polarization loss by the polarization matching depends on the XPD. In the limiting case of XPD = 0dB the gain reduces to -3dB, as indicated by the innermost circle in Figure 3, while the TD gain-dips are eliminated

The conclusion is that polarization matching performs just 1dB less than the best case of polarization TD for high XPD, and its combination with TD much recovers its gain-dip, by up-to 4dB.

5 Conclusions

The Paper considered transmit diversity techniques for mobile wireless communications. It focused on two well-known methods, TDTD and STBC. The results of this paper are applicable to both 2nd generation (IS-95) and 3rd generation systems.

The focus in this work was on polarization transmit diversity, relying on cross-polarized BS antennas. The performance gains arising from both mean power and diversity were analysed, and their interplay in the polarization transmit diversity case was presented as a function of the MS antenna orientation.

Transmit polarization matching was introduced as a relevant and most powerful method to greatly enhance the performance of any polarization transmit diversity system. It was shown that with polarization matching it is possible to improve the worst-case performance of a polarization transmit diversity scheme by up-to 4dB. Finally, it was shown that the performance of a polarization matched scheme with no transmit diversity is only 1dB inferior to that of the combined polarization transmit diversity and matching, assuming a fixed total transmitted power constraint.

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