Aspects on Space and Polarization Diversity in Wireless Communication Systems

Vasilios M. Kapinas, Maja Ilić, George K. Karagiannidis, and Milica Pejanović-Đurišić

***Abstract*—This is a synopsis of two of the most popular diversity techniques, Polarization Diversity (PD) and Space Diversity (SD), employed in modern communication systems in order to mitigate multipath fading. After outlining the basic principles of the two approaches, we provide representative samples from the literature concerning a hybrid Space-Polarization Diversity (SPD) technique, with particular application of a specific space-time block code (STBC).**

***Index Terms*—Polarization diversity, space diversity, space-time block codes, wireless communication.**

I. Introduction

The rapid growth of telecommunication industry is related to the increasing demand for a variety of multimedia services. Multiple-input multiple-output (MIMO) architecture has been proved an excellent way of enhancing the performance and capacity of wireless systems, without incurring any cost in terms of bandwidth or power [1]. Furthermore, MIMO systems offer additional degrees of diversity which can be used to combat multipath fading in a wireless channel. These salient features have rendered MIMO an indispensable part of future wireless technologies, such in fourth generation cellular networks (4G) and latest Wireless LAN standards (e.g., IEEE 802.11n standard).

However, space diversity at the base station requires antenna spacing on the order of ten wavelengths in order to provide sufficient decorrelation and hence significant improvement of the uplink performance, thus resulting in both configuration size and manufacture cost increase. Similarly, measurements show that in order to get the same diversity improvement at the remote units, it is sufficient to separate the antennas at the remote station by about half wavelength, hence rendering the mounting of multiple antennas in a single handset a quite difficult task.

The utilization of multi-branch transmit diversity schemes, with more indicative the case of the two transmit antenna system described in [2], has given the opportunity for more reliable communication in the downlink direction. Nevertheless, the required antenna spacing in the transmitter side still remains the same as in the receive diversity case, since the separation requirements for transmit diversity on one side of the link are identical to the requirements for receive diversity on the other side.

The use of dual-polarized antennas has proved to be a promising cost and space effective alternative, where two spatially separated uni-polarized antennas are replaced by a single antenna structure employing two orthogonal polarizations. Hence, the major benefit of exploiting Polarization Diversity (PD), is that the large antenna configurations of Space Diversity (SD) schemes, described above, become redundant. However, regarding portable communication, PD has the same performance as SD only in high multipath environments such as in dense urban areas [3]. Furthermore, for a vertically polarized mobile antenna such as vehicle mounted and Wireless Local Loop (WLL) applications, PD is approximately 3 dB worse in overall performance than horizontal SD [4]. Therefore, since the performance of the two above mentioned diversity techniques soundly depend on the nature of the environment (e.g., the number of scatterers), it is likely to expect a significant higher diversity gain when a hybrid Space-Polarization Diversity (SPD) multi-branch system is employed.

The organization of this paper is as follows. Section II describes the basics on PD and SD techniques. A hybrid SPD scheme initially found in [5] is outlined in Section III. Simulation results and discussion are presented in Section IV. The paper is concluded in section V.

II. Conventional Polarization and Space Diversity Techniques

A. Basic principles and types of polarization diversity

It has been shown that propagation characteristics in wireless communication systems are different for vertically and horizontally polarized waves [6]. Multiple reflections between the transmitter and the receiver lead to depolarization of radio waves, coupling some energy of the transmitted signal into the orthogonal polarized wave. Due to that characteristic of multipath radio channel, vertically/horizontally polarized transmitted waves have also horizontal/vertical component (i.e., additional diversity branch) as illustrated in Fig. 1.

In this figure, T denotes transmitted, vertically polarized wave, while R denotes received signal. Due to multipath propagation, along with the copolarized component R_y, there is also a cross-polarized component R_x. In the case of insufficient depolarization, the power imbalance between the received signal components can be very large, leading thus to low diversity gain. The parameter that indicates the power difference between the average power of the copolarized and cross-polarized signals, is denoted as cross-polar discrimination (XPD). High XPD values can lead to significant

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degradation of the system performance. Typical values of this parameter vary from $1-10$ dB in urban/suburban environment, and $10-18$ dB in rural environment [7].

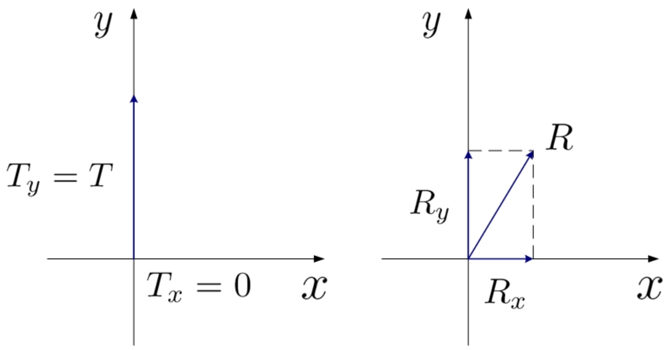

Fig. 1. The effect of depolarization due to multiple reflections.

Another very important parameter describing a polarization diversity system is the correlation coefficient between the received signal envelopes. Since polarization diversity assumes utilization of only one dual-polarized antenna, the resulted configuration necessarily leads to certain signal correlation. However, studies have shown that multiple antenna systems can achieve a significant diversity gain as long as the correlation coefficient is less than 0.7 [8]. When polarization diversity is considered, this requirement is almost always fulfilled. In fact, experimental results have shown that envelope correlation coefficient is generally even less than 0.2 [7]. Therefore, polarization diversity presents a space and cost effective solution, appearing attractive for both network operators who suffer lack of space for mounting antennas, and mobile manufacturers who provide mobile terminals with limited size.

A typical configuration of polarization diversity system consists of one transmit and one dual-polarized receive antenna (i.e., maximal diversity order of two), as illustrated in Fig. 2.

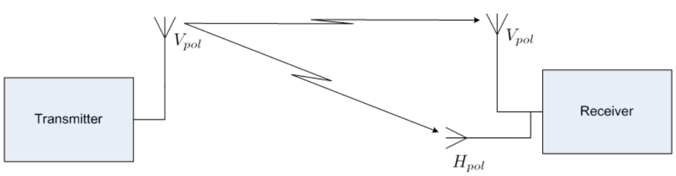

Fig. 2. Receive polarization diversity system.

In order to additionally increase diversity order, configurations with dual-polarized transmit and receive antennas are also implemented (Fig. 3).

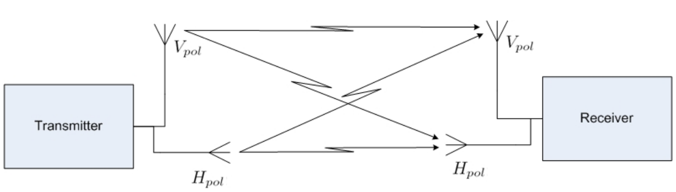

Fig. 3. Illustration of polarization diversity system with dual-polarized transmit and receive antenna.

B. Space diversity system

Communication reliability in a time-varying transmission environment can be improved by receiving the signal on two or more independent branches and particular combining of the output in some optimum manner. In the case of SD, the independent paths are artificially created by appropriate utilization of multiple antennas either at the transmitter or/and at the receiver side, leading thus to transmit diversity (Fig. 4) or/and receive diversity (Fig. 5) system designs.

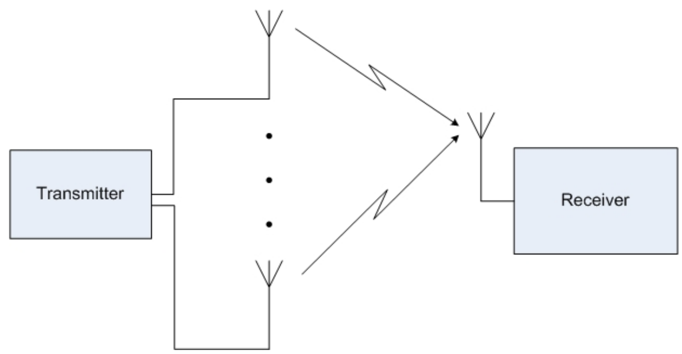

Fig. 4. Transmit diversity system.

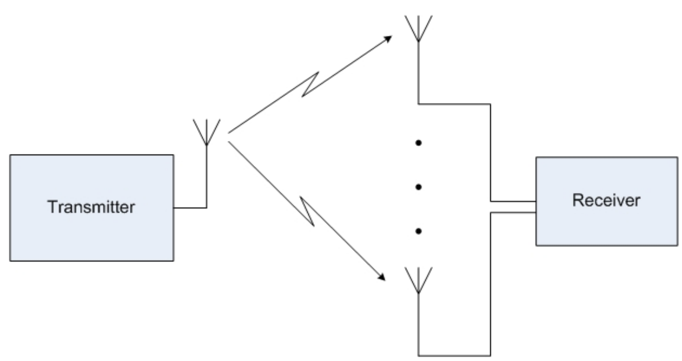

Fig. 5. Receive diversity system.

Both SD techniques exploit the lack of correlation between fades on each branch of the diversity system. The effect of spatial diversity on the system performance can be easily explained if we consider the typical graph of Fig. 6, showing the way in which the signal received on two base station antennas suffers independent fading from the two uncorrelated paths (assuming antennas at least ten wavelengths apart). At several points, the two received signals r_1 and r_2 fall momentarily below some threshold at which an acceptable SNR value is obtained. The moments at which fades occur on the first antenna are in general different from the fades occurring on the antenna of the second branch. Therefore, the overall system performance depends on the lack of correlation between fades on each branch and hence particular combining of the two replicas can lead to increased diversity gain. Such diversity combining techniques, including the optimal Maximal-Ratio Combining (MRC), Equal Gain Combining (EGC), Selection Combining (SC) and Switched Combining, are well described in [9] – [12].

From the above mentioned techniques, MRC is the most effective one in a multipath environment, as it makes optimal use of the total signal power received in all branches at any instant. This fact justifies why SD provides higher diversity gain in urban areas than it does in other environments; since there are more scatterers in urban environments, a maximal ratio combiner will make use of all the received signal energy added coherently [13].

In the case of transmit diversity, the Symbol Error Rate (SER) performance is expected to be similar to that of the previous case (receive diversity), with a 3 dB disadvantage for each branch due to the extra power needed for simultaneous symbol transmission from all transmit antennas.

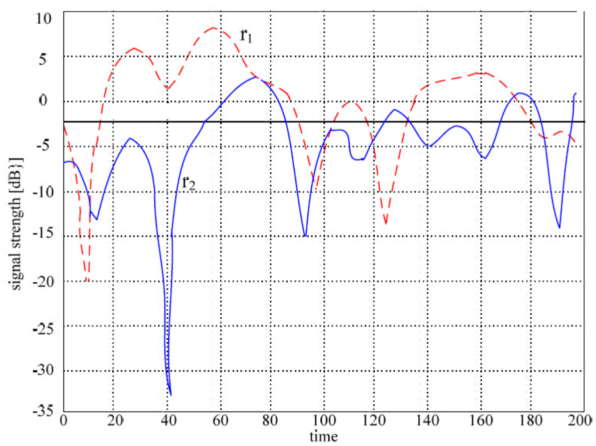

Fig. 6. Received signals from two different paths.

III. The Space-Polarization Diversity Scheme

We consider the communication link of Fig. 7 with one dual-polarized antenna at both the transmitter and the receiver side with vertical (V_{pol}) and horizontal (H_{pol}) polarization states. We assume that the encoding procedure at the transmitter employs the STBC of [2].

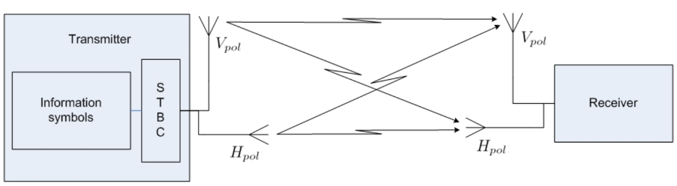

Fig. 7. Dual-polarization transmit-receive system employing STBC encoding.

Specifically, each block involves the transmission of two complex symbols s_v, s_h during one symbol period, whereas during the following symbol period, symbols $-s_h*, s_v*$ are launched with vertical and horizontal polarizations respectively.

The system model can be described by the matrix relation $\mathbf{r} = \mathbf{XH} + \mathbf{n}$, where $\mathbf{r}$ is the received matrix with entries all the signals arrived at the receiver at time instants 1 (end of 1st time slot) or 2 (end of 2nd time slot) on the two possible polarization states, $\mathbf{X}$ is the Alamouti STBC [2]. $\mathbf{H}$ presents the channel or polarization matrix involving complex Gaussian random variables of zero mean, whereas $\mathbf{n}$ stands for the complex additive white Gaussian noise (AWGN) matrix. In element wise form, the model is described by

$$\begin{pmatrix} r_{1v} & r_{1h} \\ r_{2v} & r_{2h} \end{pmatrix} = \begin{pmatrix} s_v & s_h \\ -s_h^* & s_v^* \end{pmatrix} \begin{pmatrix} h_{vv} & h_{vh} \\ h_{hv} & h_{hh} \end{pmatrix} + \begin{pmatrix} n_{1v} & n_{1h} \\ n_{2v} & n_{2h} \end{pmatrix}, \tag{1}$$

where h_{vh}, h_{hv} represent the cross couplings between the two polarization states. To proceed further, we assume a quasi-static flat fading channel with some extra limitations for the fading coefficients [14]

$$E\{|h_{vv}|^2\} = E\{|h_{hh}|^2\} = 1$$
$$E\{|h_{vh}|^2\} = E\{|h_{hv}|^2\} = \alpha$$

$$t = \frac{E\{h_{vv}h_{vh}^*\}}{\sqrt{\alpha}} = \frac{E\{h_{hv}h_{hh}^*\}}{\sqrt{\alpha}}$$
$$r = \frac{E\{h_{vv}h_{hv}^*\}}{\sqrt{\alpha}} = \frac{E\{h_{vh}h_{hh}^*\}}{\sqrt{\alpha}}, \tag{2}$$

where t, r are the transmit and receive correlation coefficients respectively and $a \in [0, 1]$ is a parameter depending on the XPD according to the relation

$$\text{XPD} = \frac{E\{|h_{vv}|^2\}}{E\{|h_{hv}|^2\}} = \frac{E\{|h_{hh}|^2\}}{E\{|h_{vh}|^2\}} = \frac{1}{\alpha}. \tag{3}$$

From equation (3), it is obvious that values of a close to unity correspond to small values of XPD and therefore high polarization diversity. It is interesting that the case of $a = 1$ (XPD(dB) $= 0$) corresponds to a "true" 2×2 MIMO system with uncorrelated fading parameters, able to provide maximum diversity order equal to 4. For $a = 0$, the system can be considered as two independent single-input single-output (SISO) systems at the origin of the loss in spatial diversity [15].

IV. Simulation Results and Discussion

Simulation results of separated works [5], [14]–[17], verify the following statements:

- The SPD scheme employing the Alamouti code outperforms the uncoded PD scheme in terms of the Bit Error Rate (BER).
- The performance of the well-known SD scheme of Alamouti degrades with the use of dual-polarized antennas. This can be explained if we consider that the new degree of freedom introduced by the polarization diversity can easily spoil the orthogonal structure of the code.
- Values of a close to unity provide the best BER with similar performance to that of the SD case for uncorrelated branches ($t = r = 0$). Actually, this ideal case is far from a realistic channel.
- Transmit and receive correlation have an identical impact on the system performance.
- Increase in either the correlation coefficients or the XPD dramatically degrades the performance of the SPD communication system (Fig. 8).
- A common consideration of a realistic channel ($a = 0.4, t = 0.5, r = 0.3$) gives BER performance loss approximately equal to 2.5 dB (Fig. 9) with respect to the ideal case ($a = 1, t = r = 0$).

V. Conclusion

In this paper, the performance of a system with one dual-polarized antenna, at both the transmitter and the receiver side with simultaneous employment of the Alamouti STBC, was compared to the traditional space and polarization diversity counterparts. The results revealed that the SPD technique outperforms the PD, but its performance deteriorates as the correlation coefficients and the XPD parameter increase. However, the replacement of the two separated antennas in either the transmitter or/and the receiver side of the classical 2×2 Alamouti scheme by a dual-polarized antenna, leads to worse BER curves. The authors estimate that future challenges in wireless communication, among others, will involve:

- Study of $2M \times 2N$ MIMO systems employing SPD antenna configurations at both the transmitter and the receiver side (with M dual-polarized T_x and N dual-polarized Rx antennas), using square orthogonal or quasi-orthogonal STBC of order M.
- Design of reconfigurable antenna arrays able to adapt their polarization (to more than two states) and geometry (by activating various dipoles) according to the special nature of each environment.

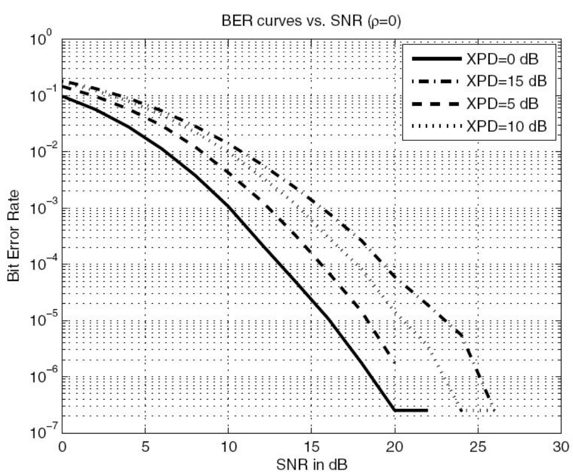

Fig. 8. Influence of XPD on BER performance for uncorrelated branches [Grau et al, 16].

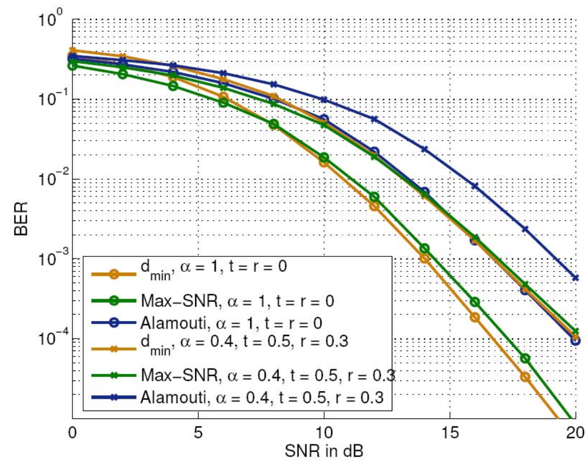

Fig. 9. Comparison between the ideal 2×2 MIMO and a realistic case [Vrigneau et al, 15][1].

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[1] This figure refers also to the other two cases of systems with full channel state information at the transmitter side (maximization of minimum Euclidean distance and maximization of the received SNR), described in [15].