Performance Assessment for the Selection Transmit Diversity in Adaptive Polarized MIMO Pre-RAKE System

Joseph V. M. Halim, Hesham El-Badawy, and Hadia M. El-Hennawy, Member, IEEE

Abstract—This paper evaluates the performance of the Selection Transmit Diversity (STD) technique in adaptive Polarized Multiple-Input Multiple-Output (MIMO) Pre-RAKE system. The proposed system will be examined in Frequency Division Duplex (FDD) mode. For the same spatial dimensions, the proposed system will be compared with the Pre/Post RAKE systems and the single-polarization Pre-RAKE STD systems. As will be shown, our system can achieve a much better performance in addition to simplify the receiver’s implementation. Also, the system performance will be investigated in case of excluding the cross-pol Pre-RAKEs in the base station. The paper discusses the effect of the polarization diversity characteristics as well as the impact of the imbalance in the co-polarized power intensities on the BER performance. For slowly-varying channels, an assessment for the system performance will be investigated under different Feedback Information (FBI) rates. In addition, a performance comparison for vehicular and pedestrian environments will be presented.

Index Terms—Multiple-Input Multiple-Output (MIMO), polarization diversity, Pre-RAKE, selection transmit diversity

I. INTRODUCTION

In mobile communications, the rapid growth of wireless voice subscribers, Internet, videoconference and the increase of using portable devices lead to have high speed, high capacity and high quality wireless communications. However, the capacity enhancement techniques, like multi-user detection, are too complex and should be avoided in downlink if the mobile stations are to be kept cheap and power thrifty. The combination between polarized MIMO and Pre-RAKE techniques is a strong candidate for the downlink wireless mobile communications. This is due to its capability of capacity enhancement without increasing the complexity and the power consumption of the mobile terminals.

Measurements have been made to investigate the performance and the configurations of the polarized MIMO channels [1]-[5]. Results show that the capacity of polarized MIMO system outperforms that of the single-polarization MIMO system with constant signal to noise ratio (SNR). The polarized MIMO system reduces the spatial dimensions where the costly spaced dipoles of the single-polarization MIMO systems are replaced by dual polarized antennas. Each dual polarized antenna consists of collocated vertical polarized and horizontal polarized antennas. Many technologies can be used to manufacturer low-cost compact-size dual polarized antennas such as microstrip and planar inverted-F (PIFA) technologies [6], [7].

In wideband polarized MIMO systems, the frequency-selective fading channel is typically experienced. Therefore, both co-pol and cross-pol RAKE receivers are required for each polarized antenna in the mobile terminal to resolve both the co-pol and the cross-pol branches. This increases the complexity and the power consumption of the mobile unit. In this paper, the co-pol and the cross-pol RAKES are moved to the Node B and consequently, the receiver is simplified.

The characteristics of the polarization diversity have been described by the cross-polarization discrimination (XPD) and the envelope correlation ($\rho_{env}$) [8]. The XPD is produced due to the depolarization of the transmitted signal by reflection, diffraction and scattering in the channel. Also, it is defined as the ratio between the cross-polarized signal power to the co-polarized signal power. In the urban and suburban environments, the XPD is normally between -1 and -10 dB, with an average of -6 dB [9], [10]. In dense environments where there is no line of sight, the XPD value approaches to 0 dB. However, the XPD in the rural environments is usually less than -10 dB, between -10 and -18 dB, due to lack of obstacles that couple the signal from one polarization into the other one [9]. Therefore, the XPD is considered as a drawback since it degrades the performance, especially in case of dense environments. In this paper, the proposed system can exploit the XPD to improve the performance by using cross-pol Pre-RAKEs in addition to the co-pol Pre-RAKEs in the Node B. Finally, $\rho_{env}$ represents the envelope correlation between the fadings experienced in the vertical and the horizontal polarization channels. The nature of electromagnetic wave
propagation dictates that the polarization orthogonal to the obstacle is attenuated more than the polarization parallel to the obstacle [9], [11]. Considering that buildings are typical obstacles in the wireless channels, the Horizontal Polarization (HPol) is expected to be attenuated more than the Vertical Polarization (VPol). The Co-polarized Power Factor (CPF) represents the impact of the imbalance in the co-polarized power intensities and it is defined as the ratio between the power of the vertical co-polarized received signal to the power of the horizontal co-polarized received signal. In this paper, the effect of XPD, $P_{\text{meas}}$, and CPF on the BER performance of the proposed system will be examined.

The Pre/Post RAKE technique was first proposed by Barreto et al. [12]. In this technique, the simple matched filter will be replaced by a Post-RAKE in the receiving side. The Pre-RAKE weights in the Pre/Post RAKE system are determined in the same way as in case of the Pre-RAKE only system. However, the Post-RAKE weights are determined by Maximal Ratio Combining (MRC) to obtain a performance gain from the remaining information in all of the peaks, not only the strongest one. Many algorithms were suggested for adapting the weights of the Pre/Post RAKE to achieve further performance gain. The eigenprecoder algorithm is introduced in [13] and the principal ratio combining (PRC) Pre/Post RAKE, which is a general expansion of the eigenprecoder, has been suggested in [14]. Since the Pre-RAKE generates $L$ pre-delayed signals and the channel produces $L$ paths, $L_y^t+L-1$ signals with different delays are received. Consequently, The Post-RAKE should be equipped with $L_y^t+L-1$ fingers to combine all of them. Therefore, when more Pre-RAKE fingers are implemented, more Post-RAKE fingers are required and the complexity of the receiver increases [14]. In this paper, a fair comparison between the proposed system and the Pre/post RAKE systems is performed in complexity and performance points of view.

In Multiple-Input Single-Output (MISO) single-polarization Pre-RAKE STD system, the best suited transmitting antenna is selected for transmission. Practically, vertical dipoles are used for the single-polarization systems since the HPol propagated signals are attenuated more than the VPol signals. In this case, such systems can be called “Vertical MISO Pre-RAKE STD systems”. For the same spatial dimension, the proposed system will be compared with the vertical MISO system.

This paper is organized as follows. In Section II, the system model is introduced. The simulation results are illustrated in Section III. Finally, the conclusion is presented in Section IV.

II. SYSTEM MODEL

In the proposed Polarized MIMO Pre-RAKE STD system, only one dual polarization group is selected for transmission. The selection rule is based on the strength of the instantaneous received co-pol signals. This is under assumption that the XPD takes certain values and consequently, the power of the cross-pol signals has no effect on the selection decision. The switching scenario will follow a different pattern. This means that in each polarization, the transmitting antenna with the strongest instantaneous co-pol received power, i.e., the highest instantaneous received Signal to Interference plus Noise Ratio (SINR), at the mobile terminal is selected for transmission. The best suited VPol and HPol antennas create the selected dual polarization group. The mobile terminal monitors the downlink channel all the time, using Training Signals (TS), transmitted from the Node B, and estimates its parameters. The mobile feeds back these parameters to the Node B from time to time, depending on the rate of the feedback, via the FBI message. The transmitter of the $k^{th}$ user in the Node B is shown in Fig. 1. After receiving the FBI message, the FBI determination and calculations unit takes the selection decision and adapts the position of the switches. Also, it provides the co-pol and the cross-pol pre-RAKEs by the calculated weights of the selected transmitting antenna in each polarization. Therefore, the $k^{th}$ user's data signal, after QPSK mapping and PN spreading stage, is multiplied by the complex conjugate of the downlink channel impulse response of the selected transmitting antenna in each polarization. It should be noted that the FBI parameters are used during the feedback waiting period till the next update instant of the FBI message. In each polarization, it is not essential that all users use the same transmitting antenna simultaneously since the Node B selects the best suited antenna for each user’s transmission.

The co-pol Pre-RAKESs are frequency-separated from the cross-pol Pre-RAKEs using orthogonal carriers to mitigate the self-interference. Orthogonal carriers $\omega_y$ are related by [15]:

$$\omega_y = \omega_x + (y-1) \frac{2\pi}{T_c}, \quad y = 1,2,3,...,Y$$

(1)

where $T_c$ is the chip duration and $Y$ is the number of carriers in the orthogonal scheme. So, the signal in the $y^{th}$ frequency band does not cause interference in the other frequency bands. For the same total transmission bandwidth, the processing gain of the orthogonal scheme ($N_y$) is given by [16]:

$$N_y = \frac{Y}{Y+1} N$$

(2)

where $N$ is the processing gain in case of the wideband DS-CDMA system. In our system, $Y=2$ such that the signals of the co-pol and cross-pol Pre-RAKEs, associated with the VPol receiving antenna, are QPSK modulated using the carrier frequency $\omega_x (y=1)$ before transmission. However, the carrier frequency $\omega_x (y=2)$ is used to modulate the signals of the co-pol and cross-pol Pre-RAKEs, associated with the HPol receiving antenna.

The channel is assumed to be a slowly-varying multipath Rayleigh fading channel with $L$ paths. For a particular downlink channel, the complex impulse response of the channel can be written as:

$$h_{k,i,j} (t) = \sum_{l=1}^{L} \beta_{k,i,j,l} e^{j \alpha_{k,i,j,l}} \delta(t - lT_c)$$

(3)

where the subscript $i$ refers to the polarization and $i=1$ is used for the VPol whereas $i=2$ is used for the HPol. Also, the subscript $x$ refers to the polarization channel and $x=1$ is
associated to the co-pol channels while $x=2$ is associated to the cross-pol channels. Therefore, $\beta_{i,\tilde{x},\tilde{r},j}$ represents the fade envelope (path gain) experienced through the $i^{th}$ path of the $\tilde{x}^{th}$ polarization channel between the $\tilde{r}^{th}$ selected transmitting antenna in the $\tilde{r}^{th}$ polarization and the $\tilde{x}^{th}$ user’s mobile terminal. It is treated as independent identically distributed (i.i.d.) Rayleigh random variable. Also, $\gamma_{i,\tilde{x},\tilde{r},j}$ is the i.i.d. uniformly-distributed phase over $[0, 2\pi]$. The delay between the successive paths equals $T_v$, assuming that the $\tilde{r}^{th}$ path has no delay. Finally, $\delta_k$ is the dirac delta function.

The selection decision rule in each polarization is given by:

$$U_{k,\tilde{x}} = \max_{1 \leq m \leq M} |U_{k,m}| = \sum_{i=1}^{K} \sum_{r=1}^{L} \beta_{i,\tilde{x},r,j}^2$$

(4)

where $U_{k,\tilde{x}}$ represents the normalization factor of the $\tilde{x}^{th}$ user in each polarization. Also, $M$ is the number of the transmitting antennas in each polarization, i.e., $M$ refers to the number of dual polarized transmit antennas in the Node B. $x=2$ represents the co-pol and cross-pol Pre-RAKEs for the selected antenna in each polarization.

The total normalization factor $U_k$ used to keep the total average transmitted power of the $k^{th}$ user constant, is expressed as:

$$U_k = \sum_{\tilde{x}} U_{k,\tilde{x}} = \sum_{\tilde{x}} \left( \sum_{i=1}^{K} \sum_{r=1}^{L} \beta_{i,\tilde{x},r,j}^2 \right)$$

(5)

So, the weights in each Pre-RAKE combiner are given by:

$$B_{i,\tilde{x},r,j} = \frac{\beta_{i,\tilde{x},r,j} e^{-j\gamma_{i,\tilde{x},r,j}}}{\sqrt{U_k}}$$

(6)

where $B_{i,\tilde{x},r,j}$ satisfies the constraint:

$$\sum_{i=1}^{K} \sum_{r=1}^{L} \sum_{j=0}^{1-1} |B_{i,\tilde{x},r,j}|^2 = 1$$

(7)

Fig. 1 The Polarized MIMO Pre-RAKE STD transmitter of the Node B.

So, the total average transmitted power of the $k^{th}$ user is kept constant and independent on $X$ and $L$. Hence, the signal transmitted from the selected transmitting antenna in each polarization for the $k^{th}$ user can be represented as:

$$s_{i,k}(t) = \frac{P_k}{U_k} \sum_{i=1}^{K} \sum_{r=1}^{L} \beta_{i,\tilde{x},r,j} b_i(t-T_v) c_i(t-T_v) e^{j(\gamma_{i,\tilde{x},r,j})} \gamma_{i,\tilde{x},r,j}$$

(8)

where $P_k$ is the transmitted power and $b_i(t)$ is the QPSK mapped sequence whose symbols $e \in \{+1,+i,-1,-i\}$. Also, $c_i(t)$ is the aperiodic PN spreading sequence with chip duration $T_v = T_c/N$ since $N$ is the processing gain and $T_c$ is the QPSK symbol duration. Each user has a unique signature sequence $c_i(t)$ different from the other users. $\alpha$ is the carrier frequency associated to either the co-pol or the cross-pol Pre-RAKEs.

A synchronous DS/CDMA system is considered for the downlink where $K$ signals are transmitted simultaneously from the Node B to $K$ users. In considering the cross-coupling between the channels, the received signals at the dual polarized receive antenna of the $k^{th}$ user’s mobile terminal are:

$$r_{i,k}(t) = \text{Re} \left\{ \sum_{i=1}^{K} \sum_{r=1}^{L} \beta_{i,\tilde{x},r,j} s_{i,k}(t-nT_c) e^{j\gamma_{i,\tilde{x},r,j}} \right\} + n_i(t)$$

(9)

Similarly:

$$r_{i,k}(t) = \text{Re} \left\{ \sum_{i=1}^{K} \sum_{r=1}^{L} \beta_{i,\tilde{x},r,j} s_{i,k}(t-nT_c) e^{j\gamma_{i,\tilde{x},r,j}} \right\} + n_k(t)$$

(10)
where $\xi_{v,\theta}$ and $\xi_{h,\theta}$ are the power intensities of both the VPoI and HPoI cross-pol signals at the $I^{th}$ user's mobile station, respectively. $n_v(t)$ and $n_h(t)$ are the Additive White Gaussian Noise (AWGN) at the receiving VPoI and HPoI antennas of the $I^{th}$ user, respectively, with zero mean and double-sided power spectral density of $N_0/2$. They represent the thermal noise of the receiver and the undesired interference signals from the other Node Bs in both polarizations.

The receiver implementation of the $I^{th}$ user's mobile station is shown in Fig. 2. The VPoI and the HPoI receiving antennas employ different frequencies where $r_v(t)$ is demodulated using the carrier frequency ($\omega_v$) while $r_h(t)$ is demodulated using the carrier frequency ($\omega_h$). Therefore, the interference from the undesired co-pol and cross-pol components transmitted to each receiving antenna will be rejected since they lie outside the operating frequency band of this antenna. It can be seen from equations (8), (9) and (10) that the channel output at each polarized receiving antenna includes $2L-1$ paths with a strong peak at $t-(L-1)T_c$ which is the desired signal in each polarization. This strong peak is the resultant of both the co-pol and the cross-pol peaks in each polarization. By combining the desired signals of both polarized receiving antennas, a very strong peak is achieved at $t-(L-1)T_c$ and only one matched filter is needed to be tuned to that peak, as shown in Fig. 2. Consequently, a significant performance gain can be accomplished due to the enhancement of the multipath, the polarization and the space selection transmit diversities, while preserving the simplicity of the receiver.

### III. Simulation Results

Computer simulations were performed to evaluate the downlink BER performance of the polarized MIMO Pre-RAKE STD system in FDD mode. In the simulation, UMTS standard is considered where the RF carrier frequency is $f_c=2$ GHz, the chip rate is $R_v=3.84$ Mcps and the QPSK modulation is applied for the data sequence. Also, the processing gain is $N=32$ chips/symbol in case of both the vertical Pre-RAKE STD system and the proposed system, without including the cross-pol Pre-RAKEs. To preserve the same transmission bandwidth, from equation (2), $N$ equals 22 chips/symbol for the proposed system using two orthogonal carriers. Both the bit and the chip waveforms are rectangular $\in [-1,1]$. Also, the mobile’s speed is $v=120$ Km/h. Therefore, the doppler spread is $B_d=v/\lambda=222$ Hz which is much smaller than the transmission bandwidth ($B<\lambda$). Consequently, the channel is considered as a slowly-varying Rayleigh fading channel. In the simulation, the mobile terminal has only one dual polarized antenna whereas the Node B has two dual polarized antennas, spaced far enough from each other to be completely uncorrelated. $P_v/P_h$ (dB) refers to the ratio between the transmitted power to the desired user and the total transmitted power from the Node B; assuming that all users have the same transmitted power. The simulation is run for $K=10$ users. The envelope correlation is $\rho_{env}=0\%$ and the FBI rate equals $1$ KHz. Finally, the number of Pre-RAKE fingers is $L_v=L_h=3$.

The first point is to compare the proposed system with the Pre/Post RAKE system, presented in the recent researches [12]-[14]. In Fig. 3, the performance comparison is performed using the same simulation parameters, presented in paper [14] where $K=1$, $N=16$, $L_v=L_h=3$. The Pre/Post RAKE system employs one vertical dipole in both the transmitter and the receiver. The proposed system replaces each dipole by dual polarized antenna in both sides. Consequently, it preserves the same spatial dimensions of the Pre/Post RAKE system. Moreover, the proposed system is evaluated under XPD=0 dB. At $10^{-3}$ BER, the PRC Pre/Post RAKE system has about 2 dB average gain over the Pre-RAKE only system. Also, it achieves a slight improvement over the MRC scheme, as shown in Fig 3. The proposed system can achieve a much performance gain over the Pre/Post RAKE systems. This is in addition to simplifying the receiver’s implementation and reducing its power consumption due to removing the Post RAKE circuit. Using nonoverlapped and orthogonal carriers, the proposed system has about 2.8 dB and 4.2 dB, respectively, average gain over the Pre/Post RAKE system at $10^{-3}$ BER. This performance improvement is attributed to the polarization diversity gain as well as the capability of the proposed system to resolve the cross-pol signals. Consequently, more independent fading are offered to the receiver causing SINR enhancement. If the space constraint allows two spatially separated transmitting antennas to be deployed, the proposed STD system can attain more performance gain. This is because the selection transmit diversity is accomplished in addition to both the multipath and the polarization diversities.

In Fig. 4, the proposed system using orthogonal carriers and XPD=0 dB is compared with the vertical Pre-RAKE STD systems. The proposed system using 1x1 dual polarized configuration can significantly outperform the 2x1 vertical MISO Pre-RAKE STD system. This is due to the higher diversity degree of the proposed system, provided by the resolved co-pol and cross-pol paths. Therefore, the polarization diversity gain of the proposed system is superior to the transmit diversity gain of the vertical MISO Pre-RAKE STD system. Also, the performance improves as the number of the dual polarized transmitting antennas increases due to the selection transmit diversity gain. In dense urban and suburban environments, the XPD approaches to 0 dB. Therefore, the
Comparison between Pol. Pre-RAKE STD and Vertical Pre/Post RAKE systems

- 1x1 vertical Pre-RAKE only [14]
- 1x1 vertical MRC Pre/Post RAKE [14]
- 1x1 dual Pol. MIMO Pre-RAKE (Nonoverlapped)
- 1x1 dual Pol. MIMO Pre-RAKE (Orthogonal)
- 2x1 dual Pol. MIMO Pre-RAKE STD (Orthogonal)

Fig. 3 A performance comparison between the polarized MIMO Pre-RAKE STD system and the vertical Pre/Post RAKE systems (MRC & PRC schemes) when $K=1$, $N=16$, $L=5$ and the FBI is done every data symbol.

Fig. 4 A performance comparison between the polarized MIMO Pre-RAKE STD system, orthogonal carriers, XPD=0 dB and the FBI rate=1 KHz.

The performance of the proposed system without including the cross-pol Pre-RakeEs is poor since the cross-pol components act as a noise. However, a significant performance gain is achieved by adding the cross-pol Pre-RakeEs in the Node B. This is due to the mitigation of the XPD noise effect and on the contrary, exploiting the cross-pol channels as resolved paths to enhance the SINR.

Fig. 5 discusses the effect of the polarization diversity characteristics on the system performance. As XPD increases, the performance improves and the lower bound of the performance is accomplished when $XPD=0$ dB. However, as $XPD$ increases, the performance degrades since the transmitting symbols during this period will increase. Therefore, the number of the transmitted symbols, which the downlink channel parameters of the FBI message will not considered as an accurate future prediction about their fading profile, will increase. This causes degradation in the BER performance. For certain FBI rate, the performance degrades as the number of users ($K$) increases due to the Multiple Access Interference (MAI).

In Fig. 8, the system performance will be examined for both the vehicular and the pedestrian environments. In this Figure, the vehicular speed is $v=120$ km/h, which refers to $B_{env}=222$ Hz whereas the pedestrian speed is $v=3$ km/h, which refers to $B_{env}=5.6$ Hz. The BER performance under vehicular speed is worse than under pedestrian speed because the fading rate of change becomes slower as the velocity decreases. This will make the downlink channel parameters of the FBI message are considered as an accurate future predicted parameters for more number of the transmitted data symbols during the FBI waiting period and consequently, the performance improves.

IV. CONCLUSION

In this paper, a novel adaptive polarized MIMO Pre-RAKE STD system is proposed for the downlink in FDD mode. For the same spatial dimensions, the proposed system, employing either nonoverlapped or orthogonal carriers, can outperform the MRC and PRC Pre/Post RAKE systems. This is in addition to reducing the complexity and the power consumption of the mobile terminal due to removing the Post-RAKE circuit. Also, our system achieves a significant performance gain over the single-polarization Pre-RAKE STD systems, having the same spatial dimensions. This is attributed to the polarization diversity gain as well as the system's capability to resolve the cross-pol signals and consequently, enhance the SINR at the mobile terminal. The system performance improves with the increase in the cross-polarization discrimination (XPD). However, the performance improvement is inversely proportional with the envelope correlation ($\rho_{env}$) and the co-pol power factor (CPF). For slowly varying channels, the BER performance improves as the FBI rate increases. Finally, the system performs better in pedestrian environment than in vehicular environment.

REFERENCES

Fig. 5 The performance of the polarized MIMO Pre-RAKE STD system under different values of XPD and CPE.

Fig. 6 The impact of the imbalance in the co-pol power intensities (CPI) on the BER performance of the polarized MIMO Pre-RAKE STD system.


Fig. 7 The performance of the polarized MIMO Pre-RAKE STD system under different FBI rates, E_{b}/N_{o}=10 dB.

Fig. 8 The performance of the polarized MIMO Pre-RAKE STD system for vehicular and pedestrian speeds, E_{b}/N_{o}=10 dB.


