DECOUPLED SPACE-TIME PROCESSING: PERFORMANCE EVALUATION FOR TDMA CELLULAR*

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ABSTRACT

In this paper, we investigate the performance of a decoupled space-time processing technique in a TDMA cellular system. This structure has, as the main characteristic, the possibility of giving more degrees of freedom to an antenna array, and it can thereby provide better co-channel interference cancellation. We analyze its performance by link-level simulations and its sensitivity for parameters like delay spread, path angle separation, Doppler frequency and signal-to-interference ratio. The results show that the decoupled space-time structure can outperform the conventional linear space-time structure, especially in cases with high level of co-channel interference.

1. INTRODUCTION

It is well known that the intersimbolic interference (ISI), which occurs due to the presence of delayed multipaths, and co-channel interference (CCI) are among the major impairments to achieve higher capacity and data rates in the mobile radio environment. The mitigation of CCI can be achieved by the use of an antenna array, which works in the spatial domain. It forms beams in the direction of arrival (DOA) of the desired signal and suppress CCI. Additionally, the antenna array is able to provide array gain and make use of the spatial diversity, if it is available, compensating the loss of signal-to-noise ratio due to fading, which is a characteristic of the mobile radio environment. It is also possible to mitigate ISI, but due to the existence of rich multipath environment, present in the mobile radio-channel, it demands too many antennas [1].

On the other hand, in order to mitigate ISI and when there is no knowledge of the channel or it is time varying, an adaptive equalizer is required. The temporal equalizer can use a finite impulse response (FIR) filter, an infinite impulse response (IIR) filter, or a Viterbi (maximum likelihood sequence estimator – MLSE) equalizer. Moreover, the use of fractionally spaced (FS), instead of symbol spaced (SS) equalizers, makes it possible to reduce CCI. However, due to fundamental limitations [1], noise enhancement may occur, leading to unsatisfactory performance.

Thus, space-only and time-only processing cannot mitigate both CCI and ISI efficiently at the same time due to their fundamental limitations. The combination of both space and time processing leads us to the space-time processing, which enables fully exploitation of spatial and temporal characteristics of the mobile radio channel and the suppression of both CCI and ISI. This is the enabling key to improve network capacity, coverage and quality.

In this paper, we use a technique where the mitigation of CCI and ISI are performed in two different stages [2] (fig. 3). The first stage is done at an antenna array, where it cancels only CCI letting ISI pass through it. The second stage is performed by a temporal equalizer, which removes ISI. By doing so, we are able to provide the array with more degrees of freedom since it does not have to discriminate the desired user multipaths that leads to ISI. Comparing with a conventional linear space-time equalizer (ST-LE) [1][3][4], this decoupled technique implies that fewer antennas can be used in order to achieve similar performance when CCI is present. This is important due to implementation complexity reasons.

Link-level performance evaluation is carried out in light of the IS-136 TDMA (time-division multiple-access) context [5] by including standard modulation, pulse shaping and channel model (two-ray Rayleigh paths) [6]. We then evaluate the performance of this structure for many different parameters such as delay spread, Doppler frequency, path angle separation, angle spread and signal-to-interference ratio (SIR). We also evaluate the performance of the ST-LE in order to compare it with the decoupled structure. Comments on how to extend the obtained results in this paper to other TDMA systems (e.g., GSM and EDGE) will also be presented.

This paper is organized as follows. In section 2 we present the system model. The decoupled space-time structure (D-ST) is briefly explained in section 3. In section 4, the results are shown. Finally, the conclusions are stated in section 5.

2. SYSTEM MODEL

The IS-136 was chosen to evaluate the performance of the decoupled structure. It uses a $\pi/4$-DQPSK (differential quadrature phase shift keying) and has the uplink slot structure depicted in figure 2. For signal processing purposes we are going to discard the first eight data symbols (D1). The Color Code is going to be considered as data, but it can be used as a training sequence.

After the training sequence, the equalizer is switched to the decision-directed mode in order to track channel variations. In our system model, we are also considering that CCI is symbol and slot synchronized with the desired user. We also assume that perfect symbol synchronization is achieved.

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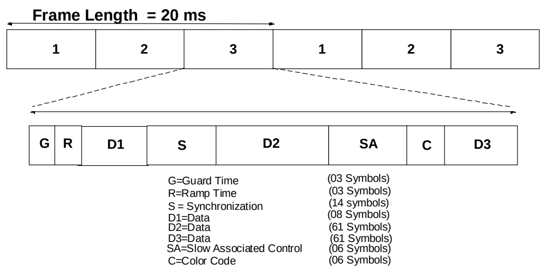

Figure 1: Uplink slot structure.

The antenna array is disposed in a uniform linear arrangement. In this case, the phase difference between two consecutive antennas associated to the n^{th} received wave is given by:

$$\phi_n = \frac{2\pi d sin(\theta_n)}{\lambda} \tag{1}$$

where θ_n is the DOA (direction of arrival) of the n^{th} wave, d is the distance between the antennas in wavelengths, and λ is the carrier wavelength. It is assumed that the first antenna has a null phase reference value. By considering $d=\lambda/2$ and M antennas, it is possible to define the antenna array response vector as:

$$\mathbf{f}(\theta) = \begin{bmatrix} 1 & e^{j\pi sin(\theta)} & \cdots & e^{j(M-1)\pi sin(\theta)} \end{bmatrix}^T \tag{2}$$

The following equation describes the Jakes [7] model for a space-time flat fading environment:

$$\mathbf{h}_f(t) = N^{-1/2} \sum_{n=1}^{N} e^{j[2\pi f_d \cos(\phi_n) + \Phi_n]} \mathbf{f}(\theta_n) \tag{3}$$

where N is the number of received waves that we assume equal to 80, Φ_n is a random phase related to the n^{th} wave's delay and uniformly distributed between 0 and 2π, θ_n is a uniformly distributed random variable, which can assume the values $[\theta-\Delta/2, \theta+\Delta/2]$, where θ is the path's DOA and Δ is the angle spread.

The angle spread plays the same role in the spatial domain as the well-known delay spread and Doppler spread concepts. It is illustrated in figure 2 along with the space-time channel model assumed in this paper. We assume that each resolvable path seen at the base station is associated with a ring of scatters around the mobile terminal, while no scattering occurs close to the base station. This model has been proposed and analyzed by a number of authors (e.g., recently in [9]) Significantly different path delays would be associated to different rings of scatters.

The mobile radio channel is usually modeled by a sum of delayed paths from a transmitter (mobile or radio station). Thus, it is possible to represent the channel impulse response as:

$$\mathbf{g}(t) = \sum_{i=0}^{paths-1} \mathbf{h}_{f_i}(t)\delta(t - t_i) \tag{4}$$

where t_i is the path delay and $\mathbf{h}_{f_i}$ is the space-time fading of the i^{th} path.

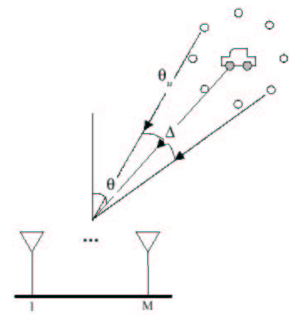

Figure 2 : Angle spread concept.

For simulation purposes, the channel model employed uses the two-path model proposed by [6] with the same average power for each path. This is considered as a worst case model for the IS-136. Hence, the space-time channel impulse response model for this case is a particular representation of (4) given by:

$$\mathbf{g}(t) = \mathbf{h}_{f0}(t)\delta(t) + \mathbf{h}_{f1}(t)\delta(t - t_d) \tag{5}$$

where t_d is the delay spread between the two paths, which is usually less than a symbol period ($T \cong 41.2\mu s$). The CCI is going to have a single path unless otherwise specified. Thus, it suffers only from flat fading, as opposed to the desired user that suffers from selective fading due to the two-path model.

In IS-136, the shaping pulse is a raised cosine with roll-off factor $\alpha = 0.35$. The raised cosine impulse response is given by:

$$\text{rcos}(t) = \frac{sinc(\frac{t}{T})\cos(\frac{\pi\alpha(t)}{T})}{(1 - \frac{4\alpha^2(t)^2}{T^2})} \tag{6}$$

Since the raised cosine impulse response has small magnitude after two symbol periods and the maximum delay spread is one symbol period, we are going to use a finite duration representation limited to $t \in$ [-2T, 2T]. Thus, our shaping pulse response, $p(t)$, can be written as:

$$p(t) = \begin{cases} r\cos(t), if -2T \le t \le 2T \\ 0 \ otherwise \end{cases} \tag{7}$$

Therefore, the overall channel impulse response, **h**, is:

$$\mathbf{h}(t) = \mathbf{g}(t) * p(t) \tag{8}$$

where $*$ means the convolution operation.

Hence, considering a single-user single-input multiple-output case, the signal received at the antenna array, **x**, is written as:

$$\mathbf{x}(t) = \sum_{k=-\infty}^{\infty} \mathbf{h}(t - kT)s(k) + \mathbf{n}(t) \tag{9}$$

where $\mathbf{n}(t)$ is the vector with additive white Gaussian noise and $s(k)$ is the desired user data.

If we consider a fractionally spaced equalizer with sampling rate of n/T, where n is an even integer larger than 1, the equivalent channel impulse response is obtained by sampling the channel at a sampling rate equal to *n/T*. We also have to make an upsampling of $s(k)$ at the same rate.

3. DECOUPLED SPACE-TIME STRUCTURE

The decoupled space-time structure studied in this paper was proposed by [2]. It aims to give more degrees of freedom to the antenna array, and thereby fewer antennas can be used to cancel the co-channel interference. This is very important to minimize implementation costs, e.g., linear amplifiers that are very expensive.

In this structure, the antenna array tries to cancel only CCI, because it is trained with a modified training sequence that should contain the ISI pattern, or something close to it, that is present in the signal received by the array. This enables the array to ignore the desired user multipaths, giving it more degrees of freedom to cancel CCI. The transversal filter that modifies the training sequence (fig. 1) is adapted with the error obtained comparing the filter and the array outputs. The array output contains ISI that is eliminated by a temporal equalizer.

Since the output of the antenna should match the ISI generated by the filter that modifies the training sequence when the error is sufficiently small, it is possible to use the coefficients of this filter as a channel estimator and so, employ them directly within the temporal equalizer. This procedure gives a performance gain as we have seen in simulations. A similar technique was employed in [8], although not in [2]. In this same framework, we also propose a MLSE instead of a DFE, making it possible to use more efficiently any available temporal diversity. The MLSE brings more reliability and performance benefits as compared to the DFE-based structure.

We compare the decoupled structure and the adaptive array followed by a DFE, shown in figure 4, where we present the radiation diagram and the output of both structures in figures 5 to 8. For these simulations we have three antennas, a signal-to-noise ratio (E_b/N_o) of 25 dB per antenna, three paths of the desired user (0^o with no delay, -20^o with a delay of $0.25T$ and 50^o with a delay of $0.5T$) and $\mathbf{h}_f=\mathbf{f}(\theta)$. Furthermore, we have two co-channel interferers (20^o and -40^o with no delay) and again, $\mathbf{h}_f=\mathbf{f}(\theta)$. The channel is a shortened version with only two non-zero coefficients in 0 and *T* seconds. It is assumed perfect symbol timing and the structure is being trained during the entire time slot.

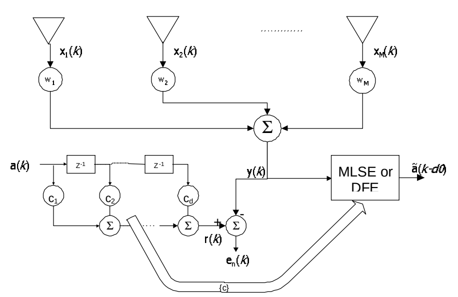

Figure 3: Decoupled Space-Time Equalizer (D-ST).

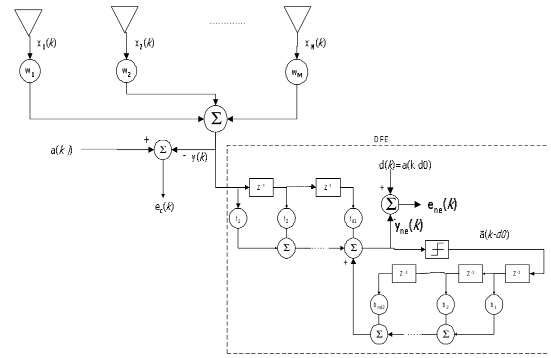

Figure 4: Adaptive Array followed by a DFE (AE)

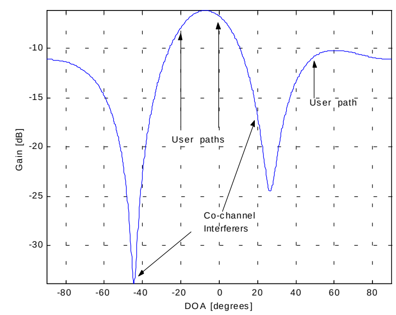

Figure 5: Radiation Diagram of the AE

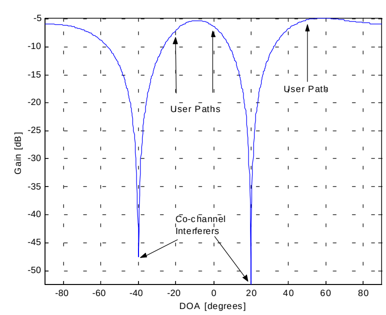

Figure 6: Radiation Diagram of the D-ST

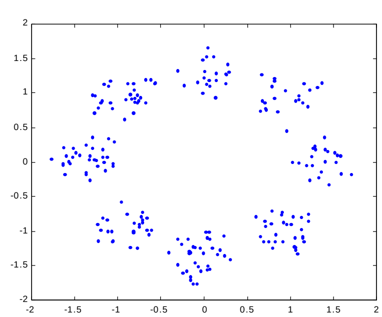

Figure 7: AE – DFE output

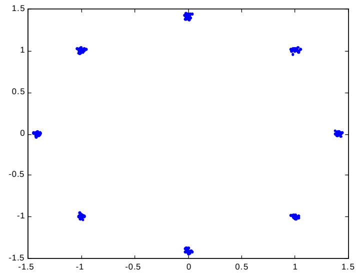

Figure 8: D-ST-DFE - DFE output

As can be seen, the decoupled structure can mitigate both ISI and CCI much better than the AE structure since it cancels only the CCI letting the ISI be cancelled by the temporal equalizer.

4. SIMULATION RESULTS

For the following simulations, the DOAs of the two-path channel are 0^o and 15^o, unless otherwise specified. The carrier frequency is equal to 900 MHz in all simulations. The angle spread is set to 0^o for both desired user and interferers paths, unless otherwise specified.

All structures have 3 antennas. The SS ST-LE has 2 coefficients per branch and the FS ST-LE has 4. The D-ST structure has 4 coefficients in the filter that modifies the training sequence and c_2 was made equal to 1 in order to avoid the null solution [2]. The D-ST-DFE has 2 coefficients in both feedforward and feedback filters. The D-ST-MLSE has the same feedforward as the D-ST-DFE and memory equal to 1.

4.1 Tracking Capabilities

Firstly, we present the results where the tracking capabilities of the structures are shown in figures 9 and 10. In these simulations the delay spread is equal to t_d=0.5T and SIR→+∞.

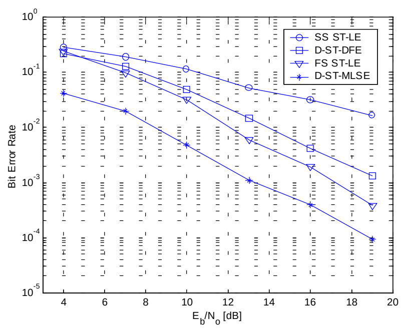

Figure 9: Tracking performance at 8 km/h (f_dT = 0.0003).

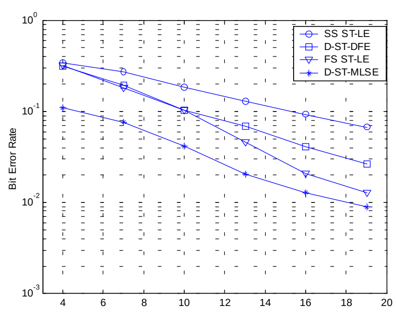

Figure 10: Tracking performance at 100 km/h (f_dT= 0.0034).

It is easily seen that all structures are sensitive to the mobile velocity. In figure 10, these higher levels of Bit Error Rate (BER) are due to the absence of spatial diversity. The poor performance of the SS ST-LE structure is due to the delay spread value, which is the worst case for this structure since the SS ST-LE cannot utilize the energy spread in multipaths as efficiently as its FS counterpart does.

4.2 Sensitivity to Delay Spread

In figures 11 and 12, we present the performance for different delay spread values. The mobile has the velocity equal to 50 km/h (f_dT = 0.0017) and the SIR→+∞ in both figures.

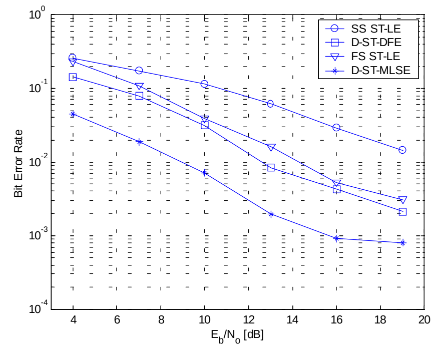

Figure 11 : Performance with t_d=0.25T

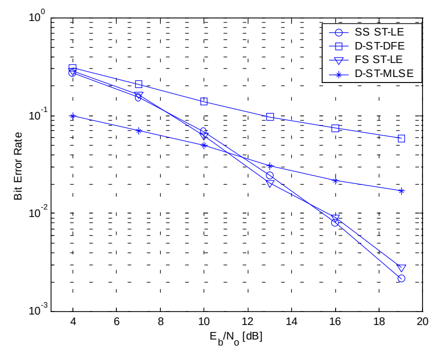

Figure 12: Performance with t_d=T.

It can be seen that the decoupled structures lose their performance with higher values of delay spread. This behavior was not expected to the D-ST-MLSE structure since the MLSE performs better with values of delay spread near one period symbol. We have realized that this erratic behavior indicates a deficiency in the acquisition of the channel coefficients. This problem affects both decoupled structures. However, further studies to improve the performance must be done, since we intend to use this decoupled technique with the EDGE system, for which the delay spread spans more than four symbols periods. One can also note that the SS ST-LE achieves a very good performance, like its FS counterpart, when t_d=T. In this case synchronization of the user paths is possible for the SS case and, thereafter, it can make fully use of the multipath diversity. It is also important to realize that the FS ST-LE has almost the same performance for both delay spread values, which should be expected, since the fractionally spaced equalizers have this characteristic.

4.3 Sensitivity to Path Angular Separation

The next results, showed in figure 13, are an example where the decoupled structures can outperform the other structures. In this situation the DOAs of the desired users are 0^o and 5^o. The delay spread is equal to $t_d=T$, the mobile has a velocity of 50 km/h and SIR$\rightarrow+\infty$.

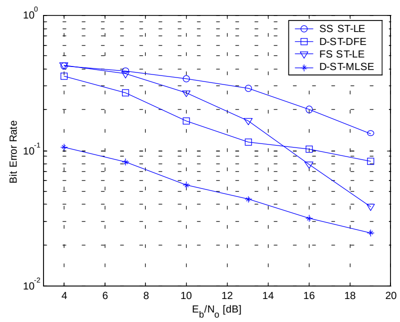

Figure 13: Performance for angular separation of 5^o.

The reason for this decrease in the performance of the conventional ST structure is that they lose the ability to work in the spatial domain. The SS structure has a higher loss when compared to the FS case due to less inherent diversity from temporal oversampling. For lower levels of angular separation, we can expect a larger difference between the performance of the conventional and decoupled structure. Indeed, when the angle spread is small, and with more than two delayed paths, the angular separation tends to diminish, and thereby the larger is the probability of having poor performance with conventional ST structures, especially the SS one. On the other hand, D-ST structures do not suffer from such degradation since the ISI caused by the delayed multipaths is mitigated by the equalizer and not by the array.

4.4 Sensitivity to Co-Channel Interference

Figures 14 and 15 shows the performance in presence of co-channel interference. For these simulations there are two independent interferers at -45^o and 50^o with only one path each one. The SIR was based on the ratio of the power of the main path of the desired user to the sum of powers of the paths of all interferers. This may be conservative since it does not take into account the power of all other paths pertaining to the desired user. SIR values were set to specific values to simulate low (17 dB) and high (5.3 dB) interference scenarios. The velocity is equal to 50 km/h for both desired user and interferers.

For a SIR of 17 dB, the performance of the D-ST-DFE is unacceptable but it is almost unchanged when compared to the situation in figure 11, where the SIR$\rightarrow+\infty$. Hence, its performance is almost unaffected by the interference showing that the decoupled technique gives a good immunity to interference. A similar behavior occurs to the D-ST-MLSE, which can outperform by far the other structures. In contrast, both SS and FS ST-LE structures are strongly affected by the interference. With a SIR of 5.3 dB, the conventional ST structures perform very poorly.

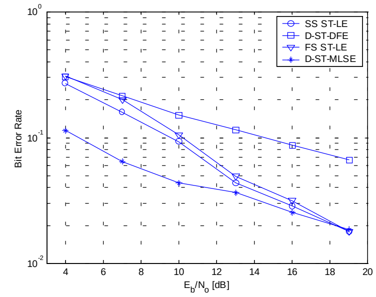

Figure 14: Performance for SIR=17 dB.

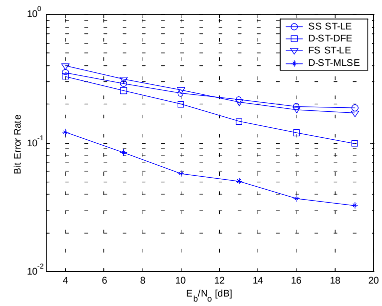

Figure 15: Performance for SIR=5.3 dB.

4.5 Sensitivity to Angle Spread

In figures 16 to 19, we show the effect of angle spread in the structures. For these two simulations, we have the same DOAs and speed used in the simulations depicted in figures 14 and 15. The SIR was set equal to 17 dB and all paths (both desired user and interferers) have the same angle spread.

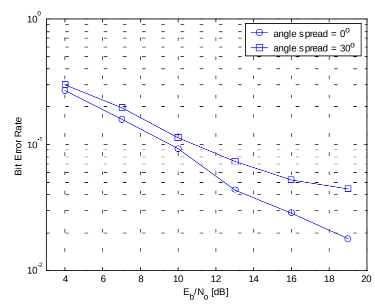

Figure 16: Radar approach *vs.* quasi-radar approach performance of the SS ST-LE.

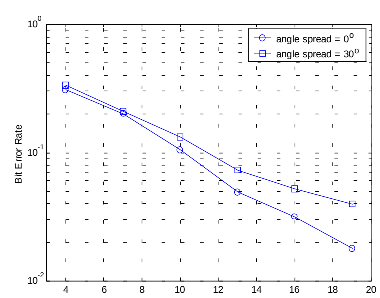

Figure 17: Radar approach *vs.* quasi-radar approach performance of the FS ST-LE.

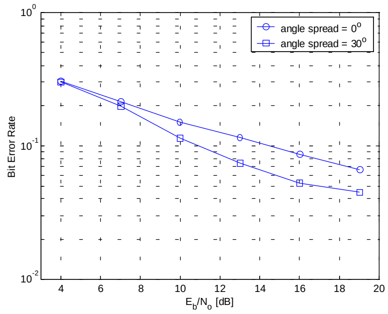

Figure 18: Radar approach *vs.* quasi-radar approach performance of the D-ST-DFE.

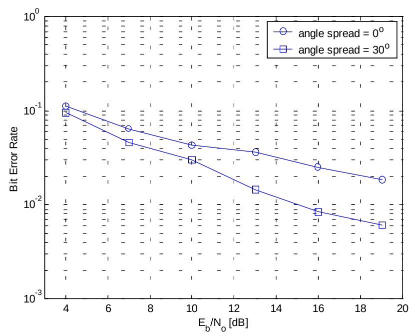

Figure 19: Radar approach *vs.* quasi-radar approach performance of the D-ST-MLSE.

It can be seen that there is a decrease in the performance of the ST-LE equalizers (both FS and SS) with the addition of angle spread. Initially, we expected an increase, since the addition of angle spread means spatial diversity. However, we suspect that the ST structure cannot make use of this spatial diversity due to the small number of antennas when compared to the number of interferers' paths. This unexpected behavior was not monotonic with the variation of the parameters, and indeed spatial diversity gains were verified in these structures for higher angle spread levels, number of antenna and interfering signal set-ups.

On the other hand, the D-ST structures behave as expected with a gain in their performances. This gain has been noticed even in scenarios where the number of interferer multipaths is equal or greater than the number of antennas, keeping the SIR at lower or intermediate levels.

5. CONCLUSION

In this paper, we have investigated the performance of a decoupled space-time technique in the light of the IS-136 TDMA system. Nonetheless, some results obtained here can be extended to other TDMA systems such as EDGE or GRPS. For instance, in the EDGE system, we intend to use the combination of the MLSE and DFE, called DDFSE (decision delayed feedback sequence estimator) for both ST (as used in reference [10]) and D-ST structures. The DFE in the DDFSE structure shortens the channel impulse response seen by the MLSE, making it possible to reduce its memory. This is very important in systems like EDGE, where the delay spread can reach more than 4 symbol periods and the computational complexity of a full MLSE to handle such delay spread may be prohibitive.

We may also try to improve the performance of the decoupled technique for higher values of delays spread. We believe that this is possible using different algorithms to adapt the antenna array and the filter that modifies the training sequence and/or using different constraints.

As shown in this paper, the D-ST technique gives more degrees of freedom to the antenna array, and it thereby can perform better than the ST-LE equalizers, as shown through simulations presented. For a prescribed performance goal, fewer antennas can be employed in this case, reducing implementation complexity. Furthermore, it can be seen that the major advantage of the decoupled structure over the conventional linear space-time structure occurs when the antenna array has its degrees of freedom overloaded, as shown in figure 15. By simulation results, we have shown that the decoupled technique has advantages over the conventional space-time structure, especially in situations with low angular separation between delayed paths and in the absence of interferers when both structures have the same number of antennas. However, further studies must be done in order to improve its performance, reducing the sensitiveness to the delay spread.

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