Performance Enhancements for DS-CDMA Receivers
Using Space-Path Diversity


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Abstract

This paper presents the performance enhancements which can be obtained using space-path diversity and interference cancellation schemes with a 4-antenna DS-CDMA receiver. The antennas used are 3 circular printed antennas and a monopole antenna placed on a pyramidal structure. The chip rate is equal to 12.5 Mchip/s and the spreading factor varying between 31 and 127. This corresponds to a bit rate between 403.225 Kbits/s and 98.425 Kbits/s for BPSK modulation.

We first characterize the delay profile of the channels and the envelope correlation between sensors from measured data. Then the performance obtained with interference cancellation schemes are characterized. The first is based on eigenfiltering and the second is a classical single sensor least squares (LS) adaptive filter. The results show that by using space-time processing, the performance is considerably increased in situations where the near-far problem is significant, and further that we can achieve high data rate transmission in a small population of users scenario.

1. Introduction

Antenna diversity is utilized in many communication systems due to its capability to reduce fading and increase the carrier-to-interference ratio. The additional improvements which can be achieved by hybrid space-path diversity schemes are analyzed by Iwai, et. al. [1]. Furthermore, Zoltowski and Ramos demonstrated that interference cancellation can be realized in CDMA PCS systems with a small number of antennas [2].

In this paper, the performance improvements which can be realized using space-path diversity and interference cancellation are characterized using a 4-antenna DS-CDMA base station receiver. Measurements are done for two transmitters at varying received power ratios. The receiver employed in these measurements does not implement power control as is commonly done in commercial DS-CDMA systems in order to quantify the effects of spatial-temporal processing as a function of the near-far power ratio.

2. Experimental Signal Scenarios

The experimental system is shown in Figure 1. Direct sequence BPSK modulated signals at the rate of 12.5 Mchips/s are transmitted from a mobile at several locations, as shown in Figure 2. Different spreading sequences, of length 31, 63 and 127, are obtained by a linear code generator with appropriate feedback connections.

The pyramidal 4-antenna receiver is placed in a room close to the window. The RF components are integrated in the receiver, which consists of one frequency translator for all four channels, in order to obtain coherent phases of the signals on each of the antennas. The frequency translator downconverts the received signals at a carrier frequency of 2 GHz to an intermediate frequency of 6.25 MHz. The signals are then sampled at a rate of 25 MHz in order to simplify the in-phase and quadrature decomposition, which is implemented by means of a finite impulse response filter.

![Experimental antenna system](Figure 1 - Experimental antenna system)

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3. Propagation Characteristics

One of the parameters which determines if space-diversity is effective, in terms of fading reduction, is the envelope correlation between the signals from each of the channels. In the case of space-diversity, the envelope correlation depends basically on the antenna separation and the angular spread, which itself depends on the surrounding scatterers of the transmitter and receiver. It should be noted that slow time variations (large scale variation due to far away obstacles) and fast variation (due to surrounding obstacles) of the signal level have an influence on envelope correlation.

The parameter which determines the efficiency of time-diversity is the delay spread, which is the measure of the time dispersion of the signal. Fading reduction can also be obtained with time diversity. Here, again, the correlation between the different resolvable paths will limit the efficiency of time-diversity for fading reduction. Considering the positions of the transmitter from Figure 2, the existence of a direct path can be expected. Nonetheless, due to the presence of metallic buildings around the transmitter, other paths can also be expected.

3.1 Envelope Correlation

Based on the measurements and the antenna separation of the system, the envelope correlation between the signals received on each antenna has been calculated. Figure 3 shows an example of one record of the envelope of the received signal on the 4 sensors. It can be seen that the fast variations of the signal are quite different from one sensor to another. However, the slow variations (long-term) have some correlation from one sensor to another. The correlation coefficients are summarized in Table 1. These coefficients are given for the case when both fast and slow fading are taken into consideration. Note, also, that the results are achieved with a compact receiver where antenna separation is 25 cm.

3.2 Impulse response

In order to determine if temporal diversity schemes can be used, it is very important to characterize the impulse response of the channel. An estimate of the impulse response of the channel convolved with the impulse responses of the transmitting and receiving filters can be obtained at the output of the matched filter. In order to improve this estimate, an average is realized over 16 periods.

The rms delay spread is calculated from these impulse responses according to the following definition:

$$\tau_{rms} = \tau_2 - \tau_1^2, \quad \text{with} \quad \tau_j = \left( \frac{\sum r_i \tau_i}{\sum r_i} \right)$$

where $r_i$ is a sample of the estimated impulse response and $\tau_i$ is the corresponding delay. The impulse responses obtained on the 4 sensors for several records are shown in Figure 4. The corresponding rms delay spreads are given for each sensor. It can be observed that most of the power of the received signal is spread out over 2 to 5 chips. Furthermore, the delay spreads are quite different from one sensor to another. This is basically due to the pyramidal structure of the antenna system, and also the channel characteristics on each sensor.
4. Interference Cancellation Schemes

Multiple Access Interference (MAI) is one of the most important limiting factors in a CDMA system. It is well known that, if MAI can be eliminated, then the system capacity can be increased significantly. MAI is even more significant when the near-far problem is encountered, which might happen because of shadowing, or because the desired user experiences multipath fading, or because of distance variations among users.

One means to combat the near-far problem is with interference cancellation schemes, and two such schemes are considered here. The first is based on interference cancellation only, and the second is a scheme which introduces diversity and also performs interference cancellation.

4.1 Single Sensor Least Squares (LS) Detector

An adaptive detector for DS-CDMA, based on the least squares error criterion, has been proposed in [3]. The receiver is a filter with a number of adaptive coefficients, equal to the spreading factor which are spaced by the duration of a chip.

This receiver has several advantages over the classical decorrelator. One of the important features which we investigate in this paper, is its resistance to the near-far problem. The LS criterion based receiver minimizes the least square error,

$$\sum_{n=0}^{N} \gamma^{n-\eta} \varepsilon(n),$$

where $\varepsilon(n) = I_k(n) - W^t(n)Y(n)$ is the error for the detected symbol $I_k(n)$ at the $n$-th symbol interval for the $k$-th user, $W^t(n)$ is the transpose vector of the adaptive coefficients of the detector and $Y(n)$ is the vector of the received signal samples during a symbol period.

It is well known that the LS solution of the coefficients is given by

$$W = R_{yy}^{-1}r_{yl_k},$$

where $R_{yy}$ is a time average of the autocorrelation matrix of the input signal and $r_{yl_k}$ is a time average of the cross correlation between the detected symbol (either training symbols or decision directed symbols) and the signal vector. The Recursive Least Squares (RLS) algorithm to update the coefficients, operating in a decision directed mode is considered in this paper. It should be noted that the update of the coefficients is done for each $i$, that is, at the symbol rate.

4.2 Space-Time interference cancellation

The space-time receiver structure is shown in Figure 5. The algorithm considered for the computation of the weights is proposed in [2]. The received signals on each sensor are processed through a digital matched filter corresponding to the user-of-interest. The theoretical output of the matched filter is shown in Figure 5. In the case of the measured signals, other impulses are observed, depending on the time dispersions of the channels. Therefore, for a given delay spread, there is a time period, $T_s$, where the useful signal is not present, and a time period, $T_{ls}$, where the useful signal is present.

During $T_s$ and $T_{ls}$, it is possible to obtain an estimate of, respectively the signal-plus-interference spatial correlation matrix, $R_{ls}$, and the interference spatial correlation matrix, $R_s$. Using these estimates, the output Signal-to-Interference-plus-Noise Ratio (SNIR) is given by [2]

$$SNIR = \frac{W_{ls}^t(R_{ls} - I_s)W}{W_{ls}^tR_sW} = \frac{W_{ls}^tR_{ls}W}{W_{ls}^tR_sW} - 1. \quad (4)$$

It is clear that, if we want to maximize the output SNIR, it is sufficient to maximize the first term of the r.h.s of expression (4)

$$\left(\frac{W_{ls}^tR_{ls}W}{W_{ls}^tR_sW}\right) \quad (5)$$

The optimum weights that maximize the SNIR are given by generalized eigenvector associated with the largest generalized eigenvalue of the matrix $R_{ls}$ and $R_s$ [2]. This is done by using the eigenvector decomposition of the matrix,

$$R_s^{-1}R_{ls}. \quad (6)$$

The metric used to characterize the performance of this receiver is the SNIR at output of the space-time filter. It is estimated using Eq. (4). The SNIRs at the output of the matched filters are estimated using a time averaged spatial correlation matrix.

5. Experimental Results

Measurements are done in the presence of two users and without power control. As discussed above, the performance is characterized by the output SNIR of the different receivers. The average SNIR on the four sensors after the matched filters is calculated. Then the output SNIR obtained with both the single sensor LS receiver and the space-time receiver are compared to that obtained with the matched filter.
5.1 Single sensor processing

The output SNIR of the single sensor LS is estimated for different records. Figure 6 shows the average output SNIR of the LS detector, for two different records, as a function of the average SNIR of the matched filter. It can be observed that at low SNIR the gain varies between 2 and 4 dB. When the SNIR increases, the LS detector tends to give the same performance as the matched filter. This is an expected behavior, since the LS detector converges to the matched filter when there is no interference. However, when functioning in a decision directed mode, if the second user’s power increases, the LS detector may lock onto the second user. This is illustrated in Figure 6, where the output LS SNIR increases at very low SNIR, thereby indicating that the LS detector is locked to the second user.

5.2 Space-Time processing

Figure 7 shows the results obtained for the case of two users. Different configurations are considered: 3 and 4 sensors and 1, 3 and 5 taps on each sensor. From these plots, it can be observed that there is a large increase in the SNIR with the space-time processing. Also, the effect of both the number of sensors and the number of taps is clearly seen.

It should be noted that the output SNIR can be expressed as follows:

$$\text{SNIR}_{out} = \frac{G P_u}{P_I + P_n},$$

where G is the diversity gain (Space-Path), $P_u$ is the useful signal’s power, $P_I$ is the second users power and $P_n$ the noise power.

When the power of the interference is low, only a diversity gain is obtained. A gain of approximately 3 dB (at 20 dB of average sensor SNIR) is achieved in going from 3 sensors to 4 sensors. When the number of taps is increased from 1 to 3, a gain of approximately 4 dB and 7 dB is achieved for the case of 3 and 4 sensors respectively. When the power of the interference increases, a large gain is obtained because of the combined effect of interference cancellation and diversity. A gain varying from 15 to 25 dB can be obtained, depending of the number of sensors and taps. In the extreme case when the interference power is too high and cannot be eliminated, a diversity gain is still obtained. This is illustrated for low average sensor SNIR and the case of 3 sensors and 1 tap on each sensor where an approximate gain of 2 dB is observed.
5.3 Effects of the length of the PN Code

Measurements are done with different lengths of the PN code. Since the chip rate is fixed at 12.5 Mcips/s, the bit rate decreases as the length of the PN code increases. Figure 8 and 9 shows the performance obtained for PN code lengths equal to 63 and 127, respectively. The results obtained are similar to the case of a spreading gain (N) equal to 31; the gain achieved varies between 15 to 25 dB for low SNIRs.

Figure 10 shows the output SNIR obtained with the matched filter and the space-time processing as a function of the relative amplitude of the second user for several records. These are plotted for the three different spreading gains: 31, 63 and 127.

![Graph showing output SNIR vs. Average sensor SNIR (Matched Filter) dB for spreading gains 63 and 127](image)

**Figure 8 - Space-Time processing for a spreading gain equal to 63**

![Graph showing output SNIR vs. Average sensor SNIR (Matched Filter) dB for spreading gain 127](image)

**Figure 9 - Space-Time processing for a spreading gain equal to 127**

It can be seen from these plots that, if we need to operate at a target SNIR of 10 dB and \(\alpha = 1\), at least a spreading factor of 127 (bit rate = 98.425 Kbits/s) should be used in the case of the matched filter. Alternately, in the case of the multisensor processing, even with a spreading gain of 31 (bit rate = 403.225 Kbits/s) the output SNIR is close to 30 dB. Therefore, in this case, we can transmit at a data rate which is at least four times higher than that achievable with a simple matched filter receiver.

![Graph showing output SNIR vs. \(\alpha\) for different spreading gains N](image)

**Figure 10 - Output SNIR in function of \(\alpha\), the relative amplitude of the second user for different spreading gains (N)**

6. Conclusion

The performance of an experimental multisensor DS-CDMA receiver has been evaluated. Measurements were done in the presence of two users with varying relative power and without power control. From the measured spread-spectrum signals, the envelope correlation between the antennas' signals and the impulse response of the channels are calculated. An correlation coefficient between 0.5 and 0.6 is obtained even when slow fading is taken into account. From the channels' impulse responses, an r.m.s delay spread varying between 2 to 5 chips is observed.

Two signal processing schemes are then implemented to eliminate the multiple access interference. The results show that a single sensor LS detector can provide around 2 to 4 dB gain compared to a classical matched filter. When space-time processing is performed, the performance is significantly improved. The combined effect of interference cancellation and diversity can provide typical gains varying between 15 to 25 dB for low SNIRs. Finally, from the results obtained, we can conclude that we can achieve high data rate transmission in a small population of users scenario.

7. References

