Multi-user Detection using a Combination of Linear Sequence Estimation and Successive Interference Cancellation

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ABSTRACT

We propose a Multi-user Detection (MUD) receiver that combines Linear Sequence Estimation (LSE) and Successive Interference Cancellation (SIC). It is based on the symbol-response model commonly employed in the context of Joint Detectors (JD). It mitigates Inter Symbol Interference (ISI) by LSE and Multiple Access Interference (MAI) via SIC. We provide numerical results that compare its performance to JD and RAKE receivers in frequency-selective fading channels. It exhibits better performance and lower complexity than existing RAKE based SIC receivers, especially in channels with large delay spreads and a large number of non-zero taps. It has a substantially lower complexity as compared to JD receivers with comparable performance under many channel conditions of interest. Key applications include burst mode WCDMA systems such as the 3GPP TDD system.

1. Introduction

The advent of 3G WCDMA systems has increased the interest in Multi-user Detection receivers. These systems operate at higher bandwidths and employ shorter codes [1]. Hence, the multi-path fading radio channel looks more frequency selective, leading to significant ISI. Also, such a channel destroys the orthogonality of these short codes, leading to large MAI. In such a scenario, conventional RAKE based receiver structures suffer significant performance degradation leading to an increased interest in MUD receivers. However, the performance advantage of MUD receivers comes at the expense of increased complexity. Hence, one of the challenges of MUD receiver design is to reduce complexity with little or no performance degradation.

Most existing MUD receivers are based upon either JD, SIC, Parallel Interference Cancellation (PIC) or a combination of these. Typically, JD receivers perform some form of LSE of the data symbols of all users [2]. The JD receivers are characterized by good performance with a high complexity that varies as the square to cube of the number of users. Although, employing an approximate Cholesky decomposition can reduce the complexity of JD algorithms with negligible loss in performance as compared to exact JD [3], still the cost becomes prohibitive for a large number of users.

SIC receivers are attractive MUD algorithms in the presence of a near-far effect [4-8]. Such a condition may exist in high capacity 3G WCDMA systems in the uplink due to poor power control and in the downlink because the Base Station (BS) may apply different gains to signals intended for different User Equipment (UE). However, most existing SIC and their hybrid flavors [4-8], have two main problems that can make them less attractive alternates to JD algorithms. First, although, in general, their complexity is less than JD receivers, but it can be higher than approximate versions of JD algorithms. Further, their complexity is very sensitive to the number of multi-path taps. In order to limit their complexity, it is common to restrict the number of taps in the channel model at the receiver to 4 or 6 taps. The second problem is that most existing SIC algorithms employ a RAKE-like receiver to detect each user’s signal, i.e., they coherently combine the various multi-path images of a user’s signal by a bank of Matched Filters, matched to each path, followed by a Maximal Ratio Combiner (MRC) [4-8]. At the end of each such detection stage, they subtract out its contribution to the overall received signal and then proceed on to detect the next stronger user, etc. While, this scheme cancels MAI, it does not cancel ISI because it implicitly assumes that the various images of a symbol are roughly confined to single symbol duration. Such an assumption is reasonable when the spreading codes are long enough and the multi-path delay spread is small compared to the symbol duration-a condition satisfied in narrow band CDMA systems. However, in certain modes of WCDMA systems, the multi-path delays can become comparable to or even larger than the symbol duration-leading to significant ISI. Now, the bank of MF followed by MRC is no longer optimal. Instead, a sequence detection of each user's symbol stream is optimal.

In this paper, we propose a MUD receiver, viz., the SIC-LSE that employs a combination of SIC and LSE. It removes both of the above mentioned problems with existing SIC. Like a SIC receiver, it detects one user at a time starting with the strongest. However, at each stage, it accounts for the ISI in each user's signal via LSE, obtains the soft and hard decisions. It uses the hard decisions to subtract out the contribution of the detected symbols to the received signal and proceeds to detect the next strongest user's signal. This leads to improved performance, especially in channels with large delay spreads, as the ISI is efficiently handled at each stage. The degree of near-far effect required for good performance is less than that required by existing RAKE based SIC receivers. In fact, the performance achieved is comparable to JD receivers for a power separation of just 1 to 2 dB. Further, the complexity of the proposed SIC-LSE receiver varies linearly with the number of users. For 8 and 16 users, it's complexity turns out to be 60% and 30%, respectively, of that of the low complexity approximate JD algorithm of [3]. Also, the complexity is less sensitive to the number of multi-path taps, allowing for a more accurate modeling of the multi-path channel.

In what follows, we describe the proposed SIC-LSE receiver and provide simulation results that compare its performance to that of the JD and RAKE-like receivers.

2. The Proposed SIC-LSE Receiver

In this Section, we first briefly review the well-known symbol-response model of a multi-user signal [2,3], which is central to the proposed algorithm. For purposes of illustration, the 3GPP UTRA TDD [1] system is assumed to be the underlying communication system.

Let there be a total of K signal bursts that arrive simultaneously at the receiver, superposed on top of each other as one burst in an observation interval. Let the i^{th} burst use code $\underline{C}^{(i)}$ of length SF chips to spread each of its N_s symbols to yield a sequence of length $SF \cdot N_s$ chips. The i^{th} burst passes through a channel with a known or estimated response, $\underline{h}^{(i)} = g^{(i)} \cdot \underline{\tilde{h}}^{(i)}$, of length W chips to form a chip sequence of length $N_c = \left(SF \cdot N_s + W - 1\right)$ long. Here, $g^{(i)}$ reflects the transmitter gain and/or path-loss and $\underline{\tilde{h}}^{(i)}$ represents the short-term fading channel between the transmitter and the receiver which is assumed to have unity average power. In the uplink, these $\underline{h}^{(i)}$, $i = 1 \cdots K$, are distinct as both, $g^{(i)}$ and $\underline{\tilde{h}}^{(i)}$ are distinct. On the other hand, in the downlink in the absence of transmit diversity, all bursts pass through the same $\tilde{h}$ but have, in general, different $g^{(i)}$. In the presence of transmit diversity in the downlink, the situation is closer to the uplink case, wherein, both, $g^{(i)}$ and $\underline{\tilde{h}}^{(i)}$ are distinct At the receiver, these channel output sequences of all users come superposed in the form of a single received vector $\underline{r}$.

It then follows from above that the multi-user model consists of N_c known received chips and $K \cdot N_s$ unknown information bearing symbols. The "symbol response", $\underline{s}^{(i)}$, of the i^{th} burst is the convolution of $\underline{C}^{(i)}$ with $\underline{h}^{(i)}$. Thus, $\underline{s}^{(i)}$ is of length $\left(SF + W - 1\right)$ chips and represents the trail of chips left by a unity symbol. Let the N_s unknown symbols of the i^{th} burst form a column vector $\underline{d}^{(i)}$ and let $\underline{r}^{(i)}$ be the contribution of this burst to the overall received chip vector $\underline{r}$. Then, the vectors $\underline{d}^{(i)}$ and $\underline{r}^{(i)}$ are related by

$$\underline{r}^{(i)} = A^{(i)} \underline{d}^{(i)},\ i = 1 \cdots K, \qquad (1)$$

where $A^{(i)}$ is a $N_c \times N_s$ matrix whose j^{th} column is the symbol-response of the j^{th} element of $\underline{d}^{(i)}$. Further, assuming a time-invariant symbol-response, each column of $A^{(i)}$ has the same support, viz., $\underline{s}^{(i)}$, and successive columns are zero-padded and shifted versions of the first column [2]. The overall, chip-rate, received vector is then,

$$\underline{r} = \sum_{i=1}^{K} \underline{r}^{(i)} + \underline{n}, \tag{2}$$

where $\underline{n}$ is the noise vector with i.i.d components with variance s^2. Note that Eq. (1) implicitly models the ISI induced by the multi-path channel on the i^{th} burst. The proposed algorithm successively estimates $\underline{r}^{(i)}$ for each and solves Eq. (1) to obtain $\hat{\underline{d}}^{(i)}$, thus effectively equalizing the channel. Thus, the SIC-LSE solves K matrix equations of dimension $N_c \times N_s$ each, as compared to the JD algorithm, which solves a matrix equation of size $N_c \times K \cdot N_s$. This leads to substantial savings in computational complexity as compared to JD. The complexity of the proposed SIC-LSE varies linearly with K whereas that of the JD varies as the cube of K. Furthermore, since the SIC-LSE optimally accounts for the ISI in each burst, it yields better performance than RAKE based SIC receivers.

The proposed algorithm consists of K stages, one stage for each burst and proceeds as follows:

1. Arrange all bursts in descending order of their received power. Without loss of generality, let $i = 1 \cdots K$ represent this order. Such an ordering can be based upon either an apriori knowledge at the receiver or by other estimation schemes commonly employed in the context of SIC/MUD receivers, e.g., burst-specific channel estimation from a burst-specific training sequence, bank of matched filters [4-6], etc. Starting with the strongest burst, viz., $i = 1$, perform the following Steps.

2. Compute $A^{(i)}$ and model the interference-corrected received vector, $\underline{x}^{(i)}$, by

$$\underline{x}^{(i)} = A^{(i)} \underline{d}^{(i)} + \underline{n}. \tag{3}$$

Note that $\underline{x}^{(1)} = \underline{r}$ and $\underline{x}^{(i)}$, $i = 2 \cdots K$, is obtained by subtracting out the contribution of all previous bursts from $\underline{r}$, as explained in Step 6. Thus, at this stage we neglect the contribution to $\underline{r}$ of all bursts weaker than the i^{th} burst.

3. Perform matched filtering on $\underline{x}^{(i)}$:

$$\underline{y}^{(i)} = A^{(i)H} \underline{x}^{(i)} \tag{4}$$

Note the matched filtering operation of Eq. (4), correlates $\underline{x}^{(i)}$ with the symbol-response of the i^{th} burst.

4. Obtain soft decisions estimates of $\underline{d}^{(i)}$ by either obtaining the least-squares (zero-forcing) solution of Eq. (4)

$$\hat{\underline{d}}^{(i)}_{soft} = \left(A^{(i)^H} A^{(i)}\right)^{-1} \underline{y}^{(i)} \tag{5a}$$

or the MMSE solution of Eq. (4),

$$\hat{\underline{d}}^{(i)}_{soft} = \left(A^{(i)^H} A^{(i)} + s^2 \cdot I\right)^{-1} \underline{y}^{(i)}, \tag{5b}$$

where I is the Identity matrix [2]. Note that in the presence of Gaussian noise, Eq. (5a) represents the maximum likelihood estimate of the soft-decision vector. Thus, both solutions are optimal linear detection schemes in the presence of ISI. Also, note that $A^{(i)^H} A^{(i)}$ is a banded Toeplitz matrix [2,3], hence, Eqs. (5a) or (5b) can be efficiently solved via well-known exact techniques. The approximate Cholesky decomposition of [3] can also be employed to efficiently solve them.

5. Convert $\hat{\underline{d}}^{(i)}_{soft}$ to hard decisions, $\hat{\underline{d}}^{(i)}_{hard}$.

6. Estimate the contribution of the i^{th} burst to $\underline{r}$, i.e.,

$$\hat{\underline{r}}^{(i)} = A^{(i)} \hat{\underline{d}}^{(i)}_{hard}. \tag{6}$$

Subtract it out from $\underline{x}^{(i)}$ to yield a new interference-corrected vector,

$$\underline{x}^{(i+1)} = \underline{x}^{(i)} - \hat{\underline{r}}^{(i)}, \tag{7}$$

for use in the next stage. Note that $\underline{x}^{(1)} = \underline{r}$.

7. Repeat Steps 2 through 6 for all stages to obtain $\hat{\underline{d}}^{(i)}_{soft}$ and $\hat{\underline{d}}^{(i)}_{hard}$, $i = 1 \cdots K$.

However, Step 6 need not be performed for the last stage.

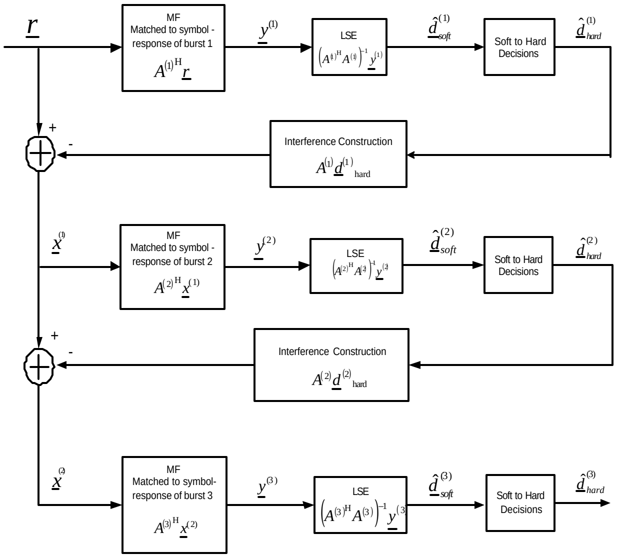

Fig. 1 Block diagram of the proposed SIC-LSE receiver with three stages corresponding to $K = 3$.

3. Numerical Results

In this Section we present simulation results that compare the Bit Error Rate (BER) performance of the SIC-LSE to the JD and RAKE-like receivers under multi-path fading channel conditions. The parameters chosen are those of the 3G WCDMA TDD system: $SF = 16$, $N_s = 61$ and $W = 57$ [1]. Each TDD burst/time-slot is 2560 chips or 667µsec long. It carries two data fields with N_s QPSK symbols each, a midamble field and a guard period. Each simulation is run over 1000 timeslots. All receivers are assumed to have exact knowledge of the channel response. The channel response is assumed to be time-invariant over a time-slot, but successive time-slots experience uncorrelated channel responses. The JD algorithm was based on [2,3], while the RAKE-like receiver was a bank of matched filters, $\hat{\underline{d}}^{(i)} = A^{(i)^H}\underline{r}^{(i)}$. Note the MRC stage is implicit in these filters because they are matched to the entire symbol-response.

Figures 2a through 2d show plots of BER vs. SNR under various multi-path fading channel conditions for $K = 8$. The BER is averaged over all bursts. Each burst is assumed to pass through an independently fading channel but all channels have the same average power leading to the same average SNR. Thus, in this case, $\underline{\tilde{h}}^{(i)}, i = 1 \cdots K$ are distinct while $g^{(i)}, i = 1 \cdots K$ are all equal. Such a situation can exist, for instance, in the uplink where the power control compensates for long-term fading and/or path-loss but not for short-term fading. At each time-slot, the bursts were arranged in power based upon the associated $\underline{h}^{(i)}, i = 1 \cdots K$. Figures 3a through 3d show similar plots. However, now, all bursts are assumed to pass through the same multi-path channel, i.e., $\underline{\tilde{h}}^{(i)}, i = 1 \cdots K$ are all equal, but with different $g^{(i)}, i = 1 \cdots K$. The $g^{(i)}$ are chosen such that, when arranged according to power, neighboring bursts have a power separation of 2 dB for Fig. 3a and 3b, and of 1 dB for Fig. 3c and 3d. Such differences in power can exist, for instance, in the downlink where the BS applies different transmit gains to bursts targeted for different UEs. As the power differential between bursts increases, the performance improves. For instance, when the power separation is increased to 2 dB in Figs. 3c and 3d, the SIC-LSE and JD curves practically overlap.

These plots show that the SIC-LSE has a performance comparable to the JD in the region of 1% to 10% BER, which is the operating region of interest for the uncoded BER. In this region, the SIC-LSE suffers a degradation of less than 1 dB as compared to the JD. The RAKE receiver exhibits significant degradation as expected, since, it does not optimally handle the ISI. Just like the average BER, the BER of individual bursts obtained from the SIC-LSE is also within a dB of the JD.

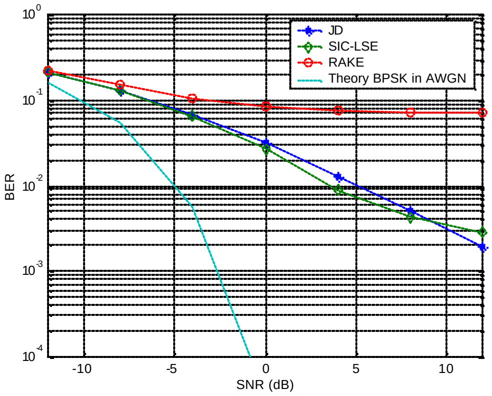

Fig. 2a Average BER vs. average SNR per burst. All 8 bursts have the same average SNR but pass through uncorrelated channels with a 3GPP WG4 Case 1 type multi-path profile [8].

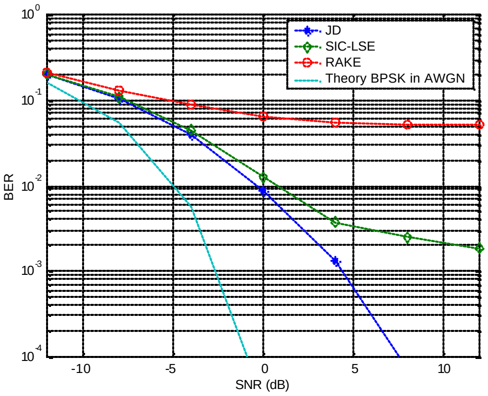

Fig. 2d Average BER vs. average SNR per burst. All 8 bursts have the same average SNR but pass through uncorrelated channels with a ITU Vehicular A type multi-path profile [9].

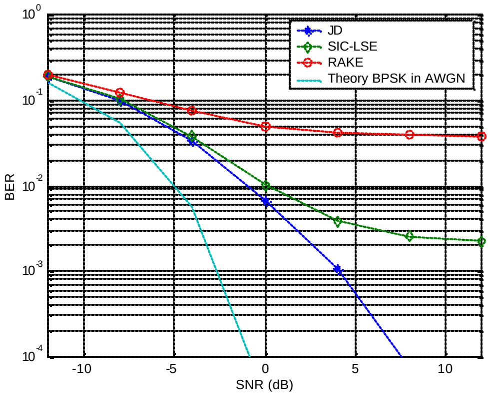

Fig. 2b Average BER vs. average SNR per burst. All 8 bursts have the same average SNR but pass through uncorrelated channels with a with a 3GPP WG4 Case 2 type multi-path profile [8].

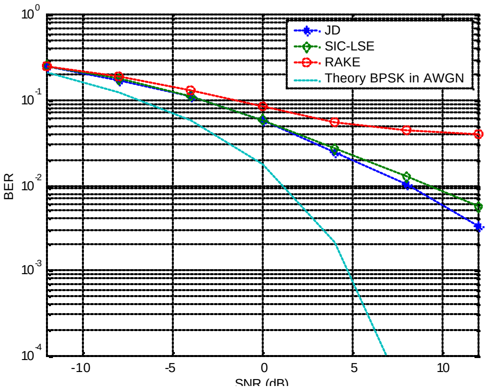

Fig. 3a Average BER vs. average SNR per burst. All 8 bursts pass through a common channel with a 3GPP WG4 Case 1 type multi-path profile [8]. Their average SNR are separated by 2 dB

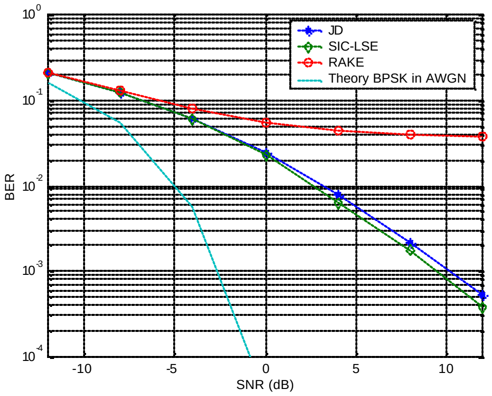

Fig. 2c Average BER vs. average SNR per burst. All 8 bursts have the same average SNR but pass through uncorrelated channels with a ITU Pedestrian A type multi-path profile [9].

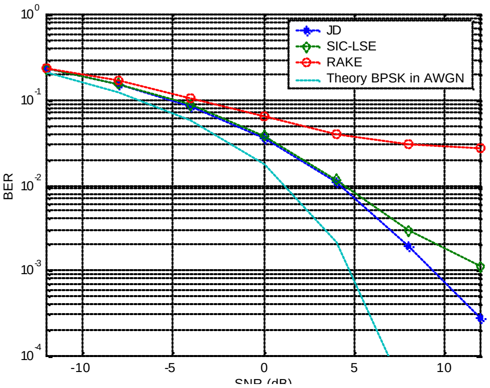

Fig. 3b Average BER vs. average SNR per burst. All 8 bursts pass through a common channel with a 3GPP WG4 Case 2 type multi-path profile [8]. Their average SNR are separated by 2 dB

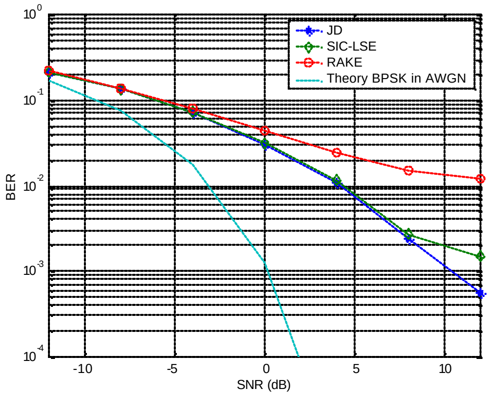

Fig. 3c Average BER vs. average SNR per burst. All 8 bursts pass through a common channel with a ITU Pedestrian A type multi-path profile [9]. Their average SNR are separated by 2 dB

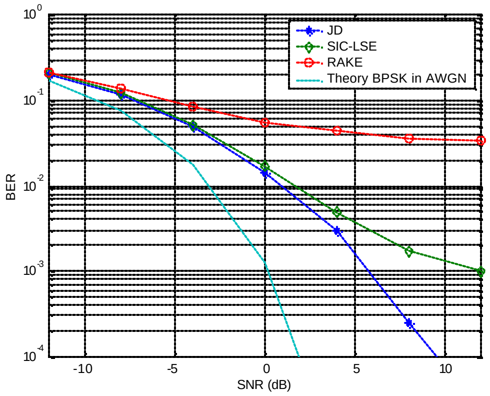

Fig. 3d Average BER vs. average SNR per burst. All 8 bursts pass through a common channel with a ITU Vehicular A type multi-path profile [9]. Their average SNR are separated by 2 dB

4. Conclusion

We proposed a MUD receiver that combines elements of LSE and SIC. It optimally detects the ISI impaired signal of each user using LSE, and cancels MAI using SIC. It has a much lower complexity than even the low-complexity approximate JD receiver [3]. Its complexity increases linearly with the number of users as opposed to complexity of the JD, which increases as the square to cube of the number of users. The performance advantage of SIC-LSE over the RAKE based SIC will increase as the channel appears more and more frequency-selective, i.e., as the ISI increases, and the complexity advantage will increase as the number of taps in the multi-path channel increase. We presented numerical results that compare the performance of the SIC-LSE with a JD and RAKE-like receiver under various channel conditions for a 3GPP TDD WCDMA system. The results show that in the operating region of interest, the SIC-LSE performs very close (within a dB) to the JD. This coupled with its lower complexity can make it an attractive candidate for MUD receivers.

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