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Abstract—In this letter, single antenna co-channel interference cancellation for cellular time-division multiple access (TDMA) networks by means of joint delayed-decision feedback sequence estimation is studied. The performance is increased by a novel adaptive state allocation technique.

Index Terms—Multiuser detection, sequence estimation, co-channel interference, interference suppression, cellular radio.

I. INTRODUCTION

Currently, single antenna co-channel interference cancellation (SAIC) is a hot topic, especially for the GSM/EDGE downlink. In field trials, tremendous capacity gains have recently been demonstrated [1], particularly for synchronous networks in urban areas. As a consequence, the upcoming GSM/EDGE release will be tightened with respect to interference cancellation [2].

One of the most challenging tasks is the design of the interference canceller, especially if (due to cost, volume, power consumption, and design aspects) only one receive antenna is available. Many interference cancellers fail if the number of receive antennas does not exceed the number of co-channels. We consider cellular TDMA systems with the following constraints:

- We focus on the downlink, where only one receive antenna is available in the mobile. (However, the proposed receiver is easily extendable to multiple receive antennas without increasing the number of states.)
- One or two dominant interferers are assumed to be present in the downlink. All other interferers are treated as noise.
- The receiver should be applicable for synchronous as well as asynchronous networks.
- Due to frequency hopping, burst-wise processing should be done.
- The receiver should be suitable for uncoded bits and for coded bits. (Note that in GSM coded (“class I”) bits and uncoded (“class II”) bits occur simultaneously.)

- Due to delay constraints, the receiver should preferably be non-iterative.
- The error performance should not be worse than for the conventional receiver ignoring co-channel interference (CCI).
- The receiver structure should be compatible with the conventional receiver.

Algorithms for co-channel interference rejection can be classified as interference cancellation techniques and multiuser detection techniques [3]. In this letter focus is on multiuser detection, because multiuser detectors typically offer a superior performance, especially in synchronous TDMA networks, and because more than two real-valued data streams can be resolved given a single receive antenna [2]. The optimal multiuser receiver in the sense of maximum-likelihood sequence detection is the so-called joint maximum-likelihood sequence estimator (JMLSE) [4], [5], [6], [7]. However, the computational complexity of the JMLSE is prohibitive, since it grows exponentially with the number of co-channels and the effective memory length of the co-channels. Numerous papers have been published in order to reduce the complexity of the JMLSE [8], [9], [10], [11], [12], [13].

In this submission, we generalize the principle of “reduced-state trellis-based equalization”, originally proposed for single-user systems [14], [15], to the multi-user case. Note that in [8], [10], [12] special cases of this general framework are considered. Related work has been published for multiple-input multiple-output (MIMO) systems in [16]. Secondly, we optimize the performance by means of “adaptive state allocation”. Emphasis is on delayed decision-feedback sequence estimation (DDFSE) [14]. For non-binary modulation, a generalization to reduced-state sequence estimation (RSSE) is straightforward by additionally applying set-partitioning of the symbol constellation [15], [16].

After introducing the equivalent discrete-time channel model under consideration, a short description of the metric used in the conventional DDFSE is given, which ignores CCI. Based on the conventional DDFSE, a joint reduced-state sequence estimator (JDDFSE) is derived, which takes CCI into account. The performance of JDDFSE can be improved by a novel adaptive state allocation technique, which is presented subsequently. Finally, numerical results are presented and conclusions are drawn.

Throughout this letter the complex baseband notation is used. Vectors are written in bold face. Estimates and hypothe-

\footnote{Strictly speaking, we should substitute “sequence estimation” by “sequence detection” throughout the letter.}
ses are denoted by (.) and (.), respectively.

II. CHANNEL MODEL

The equivalent discrete-time channel model considered in this letter is given as

\[ y[k] = \sum_{l=0}^{L} h_l[k] a[k - l] \]
\[ + \sum_{j=1}^{J} \sum_{l=0}^{L} g_{j,l}[k] b_j[k - l] + n[k] \]
\[ := x[k] + n[k], \quad 0 \leq k \leq K - 1, \]

(1)

where \( y[k] \in \mathcal{C} \) is the \( k \)-th baud-rate output sample of the analog receive filter, \( L \) is the effective memory length of the discrete-time intersymbol interference (ISI) channel model, \( h_l[k] \in \mathcal{C} \) are the channel coefficients of the desired user \( (E \| h[k] \|^2 = 1) \), and \( g_{j,l}[k] \in \mathcal{C} \) are the channel coefficients of the \( j \)-th interferer, \( 1 \leq j \leq J \), \( J \) is the number of interferers, \( a[k] \) is the \( k \)-th data symbol of the desired user, \( b_j[k] \) is the \( k \)-th data symbol of the \( j \)-th interferer, both randomly drawn from an \( M \)-ary alphabet \( (E \| a[k] \|^2 = 0) \). The \( n[k] \) \( \in \mathcal{C} \) is the \( k \)-th sample of a Gaussian noise process \( (E \| n[k] \|^2 = 0) \). \( x \) is the time index, and \( K \) is the number of \( M \)-ary data symbols per burst. All random processes are assumed to be mutually independent. The data symbols are assumed to be independent and uniformly distributed. The channel coefficients \( h[k] := [h_0[k], \ldots, h_L[k]]^T \) and \( g_{j,l}[k] := [g_{j,0}[k], \ldots, g_{j,L}[k]]^T \) comprise pulse shaping, the respective physical channel, analog receive filtering, the sampling phase, and the sampling rate. The signal-to-interference power ratio is defined as \( C/I := E \| h[k] \|^2 / \sum_{j=1}^{J} E \| g_{j,l}[k] \|^2 \).

Without loss of generality, the effective memory length, \( L \), is assumed to be the same for all co-channels. Possibly, some coefficients are zero. In case of square-root Nyquist receive filtering and baud-rate sampling, the Gaussian noise process is white. This case is assumed in the following. The equivalent discrete-time channel model is suitable for both synchronous and asynchronous TDMA networks, because time-varying channel coefficients are considered.

III. MULTIUSER DETECTOR DESIGN AND OPTIMIZATION

A. Delayed Decision-Feedback Sequence Estimation (DDFSE)

First, let us consider the case of no co-channel interference. The corresponding baud-rate equivalent discrete-time channel model simplifies as

\[ y[k] = \sum_{l=0}^{L} h_l[k] a[k - l] + n[k], \quad 0 \leq k \leq K - 1. \]

(2)

For additive white Gaussian noise, the DDFSE is defined as [14], [15]

\[ \hat{a} = \arg \min_a \sum_k \left| y[k] - \sum_{l=0}^{L} h_l[k] \hat{a}[k - l] \right|^2, \]

(3)

where \( K \) is a design parameter \((0 \leq K \leq L)\). The number of states is \( M^K \). The postcursor ISI in the third term in (3) is taken into account by state-dependent decision feedback (usually called “parallel decision feedback equalization, PDFE”).

B. Joint Delayed Decision-Feedback Sequence Estimation (JDDFSE)

Now, consider the case of \( J = 1 \) dominant interferer for the purpose of derivation of the JDDFSE:

\[ y[k] = \sum_{l=0}^{L} h_l[k] a[k - l] + \sum_{l=0}^{L} g_{1,l}[k] b[k - l] + n[k], \]
\[ 0 \leq k \leq K - 1. \]

(4)

A generalization to multiple interferers is straightforward. For convenience, the index \( j \) is dropped. Let us assume that the channel coefficients \( h[k] \) and \( g[k] \) are known at the receiver. For additive white Gaussian noise, the JDDFSE can be defined as

\[ (\hat{a}, \hat{b}) = \arg \min_{(a,b)} \sum_k \left| y[k] - \sum_{l=0}^{L} h_l[k] \hat{a}[k - l] - \sum_{l=0}^{L} g_{1,l}[k] \hat{b}[k - l] \right|^2, \]

(5)

where \( K_d \) and \( K_i \) are design parameters, which can be chosen independently within the range \( 0 \leq K_d, K_i \leq L \). (In the general case, one design parameter is needed for each of the \( J + 1 \) co-channels.) The total number of states is \( M^{K_d+K_i} \), where \( M^{K_d} \) corresponds to the number of states of the desired user and \( M^{K_i} \) to the number of states of the dominant interferer. The postcursor ISI in the last term in (5) is taken into account by state-dependent decision feedback (called “joint parallel decision feedback equalization, JPDFE”). For \( K_d = K_i = 0 \), the joint decision feedback equalizer (JDFE) is obtained. The other extreme is \( K_d = K_i = L \), where the joint maximum-likelihood sequence estimator is obtained.

C. Adaptive State Allocation

As pointed out in the previous subsection, the design parameters \( K_d \) and \( K_i \) can be chosen independently. This provides many degrees of freedom. For example, if the total number of states is fixed to be \( M^{K_d+K_i} = 2^{K_d+K_i} = 16 \),
possible choices are \((K_d = 0, K_i = 4), (K_d = 1, K_i = 3), (K_d = 2, K_i = 2), (K_d = 3, K_i = 1),\) and \((K_d = 4, K_i = 0)\). Conventionally, one would select the design parameters so that on average the error rate is low.

An alternative approach is to optimize the design parameters for each burst given a fixed number of states and given \(h[k]\) and \(g[k]\). Let us again assume that the total number of states is 16, i.e., \(K_d + K_i = 4\). If the dominant interferer is weak with respect to the desired user, \((K_d = 3, K_i = 1)\) or \((K_d = 4, K_i = 0)\) should be selected. Vice versa, if the dominant interferer is strong with respect to the desired user, \((K_d = 0, K_i = 4)\) or \((K_d = 1, K_i = 3)\) may be the better choice. This concept is dubbed adaptive state allocation (ASA). Given essentially the same computational complexity compared to a fixed allocation (plus some overhead for the selection rule), a lower average error rate can be achieved. As a suitable selection criterion, the minimum squared Euclidean distance \(d_{\text{min}}^2\) between possible paths in the reduced-state joint trellis is chosen here since the signal-to-noise ratio is typically large. Other selection criteria may be chosen as well, particularly in the nonbinary case.

In [17], an adaptive state allocation scheme has been proposed for single-user receivers. The number of states is adapted to the short-term received power, whereas in our approach the total number of states (and hence the computational complexity) is constant. As opposed to [17], no optimization of thresholds is needed.

The proposed adaptive state allocation technique can be described as follows for \(J = 1\) interferer: In the noiseless case, the squared Euclidean distance between the transmitted sequence \(x = [x[0], x[1], \ldots, x[K - 1]]\) and any other sequence \(\tilde{x} = [\tilde{x}[0], \tilde{x}[1], \ldots, \tilde{x}[K - 1]]\) is given as

\[
d^2(h[k], g[k], K_d, K_i) = \sum_k |x[k] - \tilde{x}[k]|^2
\]

\[
= \sum_k \left| \sum_{l=0}^{K_d} h_l[k] a[k-l] + \sum_{l=0}^{K_i} g_l[k] b[k-l] \right|^2
- \sum_{l=0}^{K_d} h_l[k] a[k-l] - \sum_{l=0}^{K_i} g_l[k] b[k-l]|^2
\]

\[
= \sum_k \left| \sum_{l=0}^{K_d} h_l[k] (a[k-l] - \tilde{a}[k-l]) \right|^2
+ \sum_{l=0}^{K_i} g_l[k] (b[k-l] - \tilde{b}[k-l]) |^2,
\]

where \(\alpha[k]\) and \(\beta[k]\) are called difference symbols of desired user and interferer, respectively, at time index \(k\). (For systems with binary antipodal modulation, \(\alpha[k], \beta[k] \in \{0, +2, -2\}\).)

In order to simplify the computations, in (6) it is assumed that the JPDFE-part of the metric (c.f., (5)) cancels out due to correct decisions. The computation of the minimum squared Euclidean distance,

\[
d_{\text{min}}^2(h[k], g[k], K_d, K_i) = \min_{\alpha[\cdot], \beta[\cdot], \alpha[0] \neq 0} \left( \sum_k \left| \sum_{l=0}^{K_d} h_l[k] \alpha[k-l] + \sum_{l=0}^{K_i} g_l[k] \beta[k-l] \right|^2 \right),
\]

can be done in the so-called difference trellis (for example by means of the Viterbi algorithm) or in a state diagram (for example by means of the Dijkstra algorithm). For systems with binary antipodal modulation, the difference trellis has \(3^{K_d+K_i}\) states. Symmetries can be exploited to reduce the number of states without performance loss. Typically, the error events do not exceed two times the constraint length \(L+1\). The selection rule for adaptive state allocation is given by

\[
(K_d, K_i) = \arg \max_{(K_d, K_i) : K_d+K_i = \text{const}} d_{\text{min}}^2(h[k], g[k], K_d, K_i).
\]

The minimum squared Euclidean distance can also be used as an indicator for the instantaneous bit error probability of the desired user:

\[
P_b \sim Q \left( \frac{d_{\text{min}}^2(h[k], g[k], K_d, K_i)}{2N_0/E_s} \right)
\]

\[
(7)
\]

\[
IV. \text{NUMERICAL RESULTS}
\]

For the numerical results presented in Fig. 1, a synchronous GSM network with \(J = 1\) dominant interferer is assumed. The number of the training sequence code (TSC) of the desired user is assumed to be uniformly distributed over all 8 possible sequences specified for GSM. The same applies to the TSC of the dominant interferer, with the exception that it is assumed to be different from the TSC of the desired user; this scenario can be managed by the network operator. Since co-channel interference is particularly a problem in densely populated areas, the GSM 05.05 typical urban (TU) channel model is chosen, which is characterized by an effective channel memory length of \(L = 3\) (plus residual ISI). In order to provide reliable results, \(5 \cdot 10^4\) statistically independent bursts have been generated (block fading). A JDDSFSE equalizer with 16 states is used, both with and without adaptive state allocation. Since \(L = 3\), \((K_d = 4, K_i = 0)\) and \((K_d = 0, K_i = 4)\) has not been implemented. The overhead for computing the minimum squared Euclidean distance could be kept well below 20%. As a benchmark, performance results for the conventional receiver
ignoring CCI ($2^L = 8$ states) and for JMLSE ($2^{2L} = 64$ states) are included in Fig. 1 as well. Perfect channel knowledge is assumed, since channel estimation is beyond the scope of this letter. Given perfect channel knowledge, numerical results for asynchronous networks are virtually identical.

As indicated in Fig. 1, with manageable complexity near-optimum performance can be obtained even without additional adaptive prefiltering for the purpose of channel shortening\(^2\) [10]. Since the power control for the interferer(s) can not be perfect, the interference varies over a large range. As a consequence, the error performance should be “flat” over a large range of $C/I$ values, which is well achieved by the proposed receiver.

In Fig. 2, the relative frequency of the parameters $K_d$ and $K_i$ in case of ASA is plotted for the same scenario as described above. It is interesting to note that the optimum $K_d$ does not monotonically decrease with decreasing $C/I$. Hence, the average $C/I$ is not the right criterion in order to optimize $K_d$. Although the data stream of the desired user is of primary importance, at $C/I \approx 0\ldots5$ dB in about 50% of the cases ($K_d = 3, K_i = 1$) is not the best choice. ASA is particularly efficient in this interesting range of $C/I$ values.

V. CONCLUSIONS

In this letter a class of reduced-state trellis-based multiuser detectors, called joint reduced-state delayed decision-feedback estimation (JDDFSE), is described and explored for the purpose of SAIC. The aim of JDDFSE is to eliminate co-channel interference and intersymbol interference jointly. In contrast to the JMLSE, the complexity/performance trade-off of JDDFSE is adjustable. Especially in conjunction with adaptive state allocation, a computational complexity can be achieved which is comparable to the complexity of a conventional GSM receiver neglecting co-channel interference, although the performance loss compared to JMLSE is small.

\(^2\)Channel shortening is useful for nonbinary modulation schemes, however.

The concept of JDDFSE can easily be generalized to joint reduced-state sequence estimation (JRSSE). The algorithm can also easily be modified to deliver soft outputs.

References


